Controlled Release Environmental Reactants:

A More Efficient Approach to In Situ Remediation

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Controlled Release Reactants

What are the Methods and Materials?

SPECIALTY EARTH SCIENCES, LLC

3rd Party Validation

Independently researched and published by several universities including:

- Ohio State
- Purdue
- University of Nebraska
- Clemson
- Colorado School of Mines
- UNC A&T
- Clarkson University

3rd Party Validation

Currently the subject of DOD/DOE field study: ESTCP Proj# ER-201324

- "Sustained In Situ Chemical Oxidation (ISCO) of <u>1,4-Dioxane</u> Using Slow Release Chemical Oxidant Cylinders"
- Demonstration Site: Naval Air Station North Island (**San Diego**)

References:

Links to 3rd party publications can also be found on our website at:

www.sesciences.com/technical-library

Specialty Earth Sciences IP:

US Patent No: 7,431,849
US Patent No: 8,210,773
US Patent No: 8,366,350
US Patent No: 9,061,333
US Patent No: 9,611,421
Japanese Patent No: 6,058,708
US Pat App No: 12-269,520
US Pat App No: 14-024,046
US Pat App No: 14-920,370
US Pat App No: 15-450,369
US Pat App No: 15-342,845
US Pat App No: 15-014,308
US Pat App No: 15-198,702
EU Pat App No: 09 826 642.2-1371

- Yang 2016 – "To postpone the precipitation of manganese oxides in the degradation of tetrachloroethylene by controlling the permanganate concentration"
  - http://dx.doi.org/10.1080/09593330.2016.1184320
- Chainarong 2016 – "Oxidation of 17B-Estradiol in Water by Slow-Release Permanganate Candles"
  - http://doi:10.1089/ees.2015.0456
- Yao 2016 – "Radial basis function simulation of slow-release permanganate for groundwater remediation via oxidation"
  - https://doi.org/10.1016/j.cam.2016.02.006
- Chanat 2015 – "Treating Methyl Orange in a Two-Dimensional Flow Tank by In Situ Chemical Oxidation Using Slow-Release Persulfate Activated with Zero-Valent Iron"
  - http://doi:10.1089/ees.2015.0110
- Rauscher 2012 – "Using slow-release permanganate candles to remediate PAH-contaminated water"
  - https://doi.org/10.1016/j.jhazmat.2012.09.064
- Kambhu 2012 - "Developing slow-release persulfate candles to treat BTEX contaminated groundwater."
  - http://dx.doi.org/10.1016/j.chemosphere.2012.06.004
- Christenson 2012 - "Using slow-release permanganate candles to remove TCE from a low permeable aquifer at a former landfill."
  - http://dx.doi.org/10.1016/j.chemosphere.2012.06.009
- Woo 2009 "Characteristics of permanganate oxidation of TCE at low reagent concentrations." Environmental Technology
  - http://dx.doi.org/10.1080/09593330902840342
- Luster-Teasley 2009 - "Encapsulation of Potassium Permanganate Oxidant in Polymers"
  - http://books.google.com/books?id=RYE6YKPdFDEC&lpg=PA278&ots=pd_BMxiUaZ&dq=Luster%20teasley%20proceedings%20of%202007&pg=PA278#v=onepage&q=Luster%20teasley%20proceedings%20of%202007&f=false
- Lee 2007 - "Efficacy of controlled-release KMnO4 (CRP) for controlling dissolved TCE plume in groundwater: A large flow-tank study
  - http://dx.doi.org/10.1016/j.chemosphere.2008.10.062
- Lee 2007 - "Characterization and optimization of long-term controlled release system for groundwater remediation: a generalized modeling approach"
  - http://dx.doi.org/10.1016/j.chemosphere.2007.04.037
- Lee 2007 - "Characteristics and applications of controlled-release permanganate for groundwater remediation"
  - http://dx.doi.org/10.1016/j.chemosphere.2006.09.093
- Ross 2005 - "Characteristics of Potassium Permanganate Encapsulated in Polymer"
  - http://dx.doi.org/10.1061/(ASCE)0733-9372(2005)131:8(1203)

Key Concepts:

<u>CONTROL IMPLEMENTATION COSTS:</u>

- No expensive injection field services required
- Use your preferred driller
- Implementation can be achieved by on-site consultant

<u>CONTROL REACTANT DISTRIBUTION:</u>

- Apply reactants where they belong without guessing where chemical is going
- Apply reactants in sufficient mass required (Ex: 500 lbs oxidant in 10’x10” auger boring)

Technology

- **Safer and more effective** approach to ISCO

- Delivers high concentration reactants to the target and remains active for **longer periods** of time (several months to a couple of years – depending on material selection)

- Addresses the **common problems and technical challenges** encountered with traditional pressurized liquid injection applications:

1. **Relatively short period of oxidant activity in subsurface**
2. **Contaminant contact problems - injected oxidants take the path of least resistance (flow-by)**
3. **Problem geologies: low permeable media (LPM)**
4. **Site logistics – ISCO events are cumbersome and can be disruptive to active facilities**

Technology

- Involves coating or encapsulating granular environmental reactants for a **more efficient** and **user-friendly** implementation

- These materials can be applied to the subsurface in a **number of forms and methods……..**

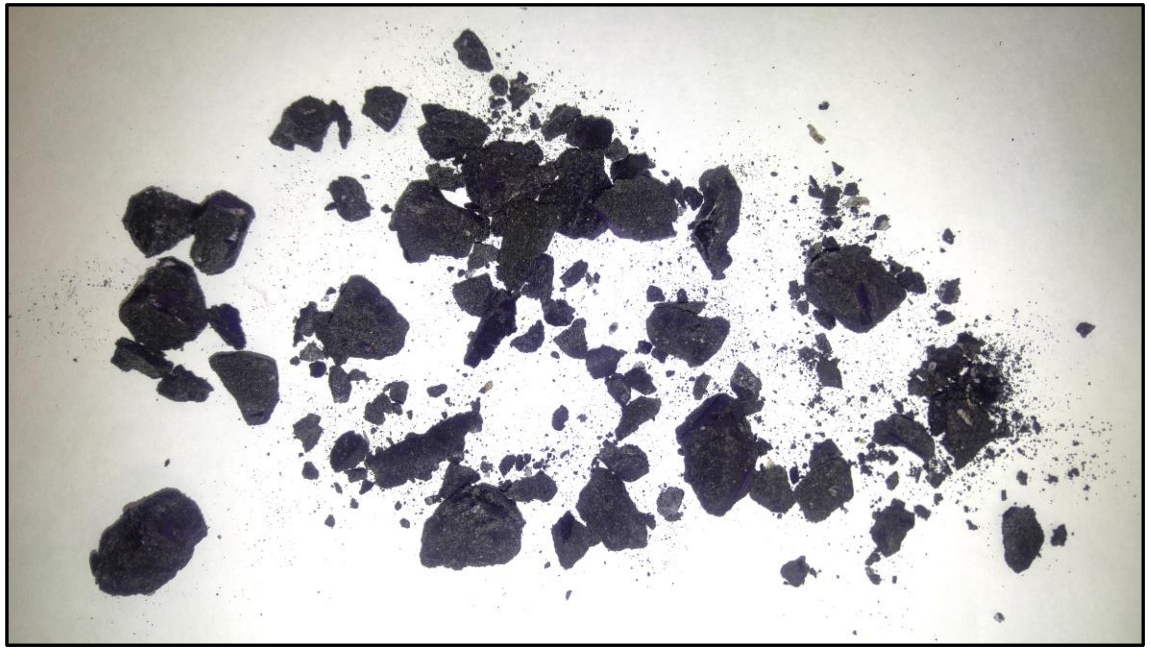
MULTIPLE <u>SHAPES</u>

MULTIPLE <u>SIZES</u>

SEVERAL <u>CHEMISTRIES</u>

Material Forms

- Cylinders
- Spheres
- Granules
- Pellets



Installation Methods

Horizontal Wells

Direct Borehole Installation

Down-Well Installation

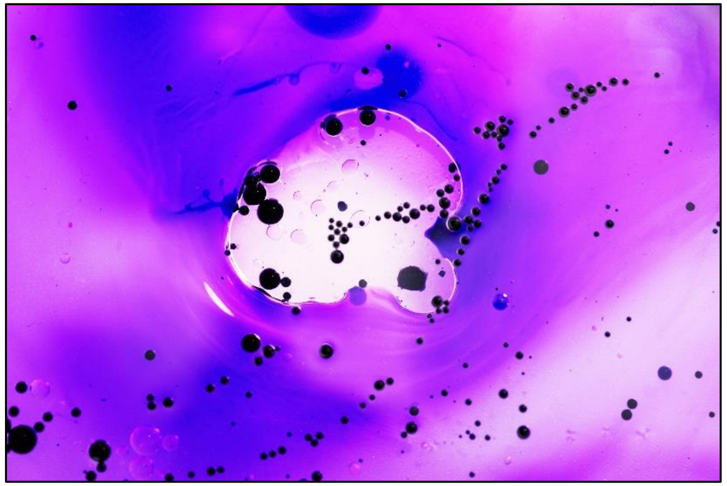
Excavation Closure

Mechanism Of Reactant Release

1) Sustained Reactant Release

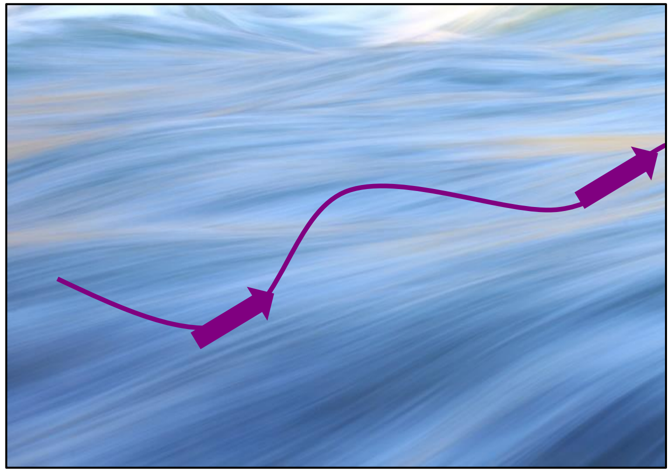
Slow/sustained reactant release over time is the prevailing MRR in **dissolved phase contaminant conditions**

2) Targeted Reactant Release

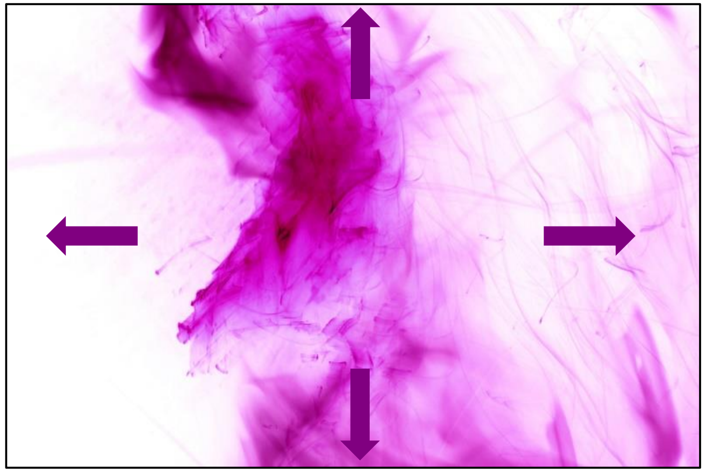


- **In the presence of NAPL** reactants will be preferentially released in high concentration
- Targeted release is governed by the effects of hydrocarbon partitioning

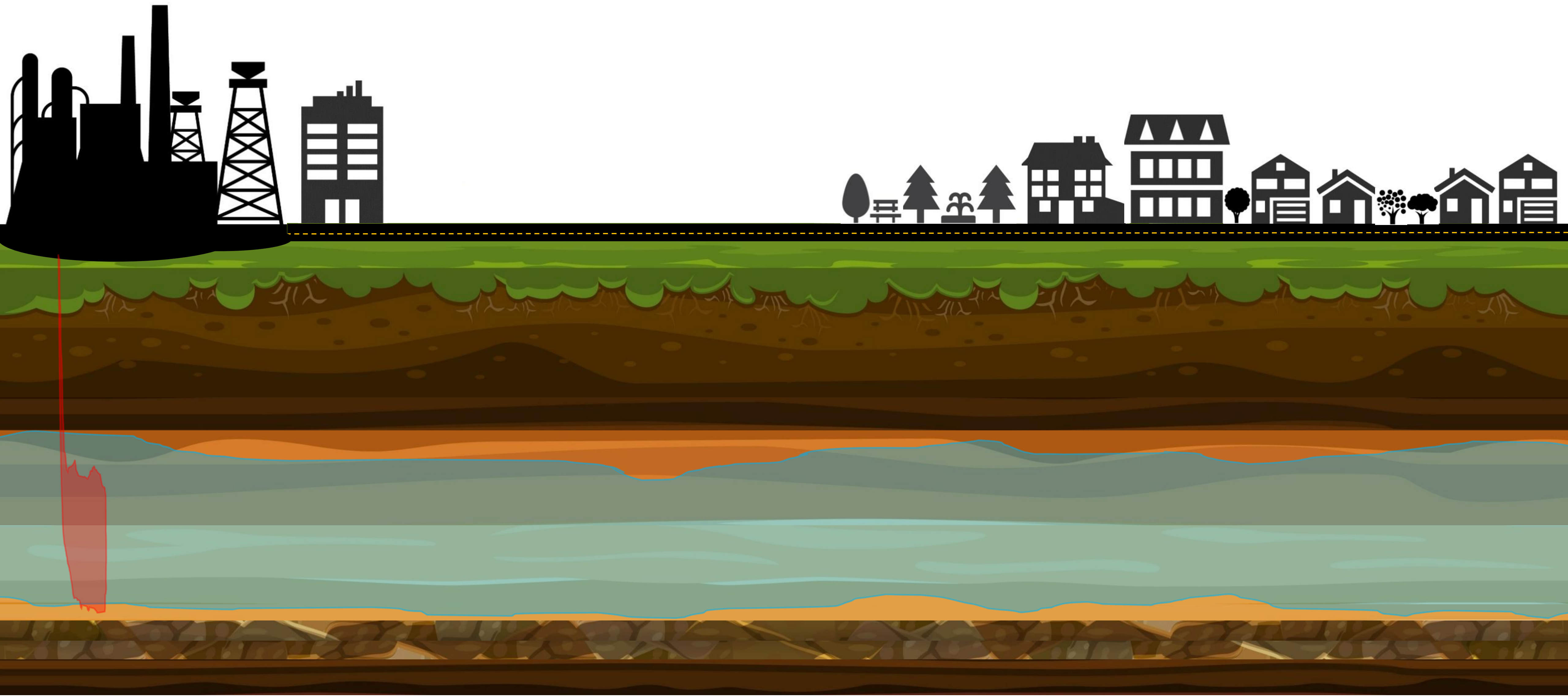
1. **Advective flow** governs reactant transport in **transmissive** formations



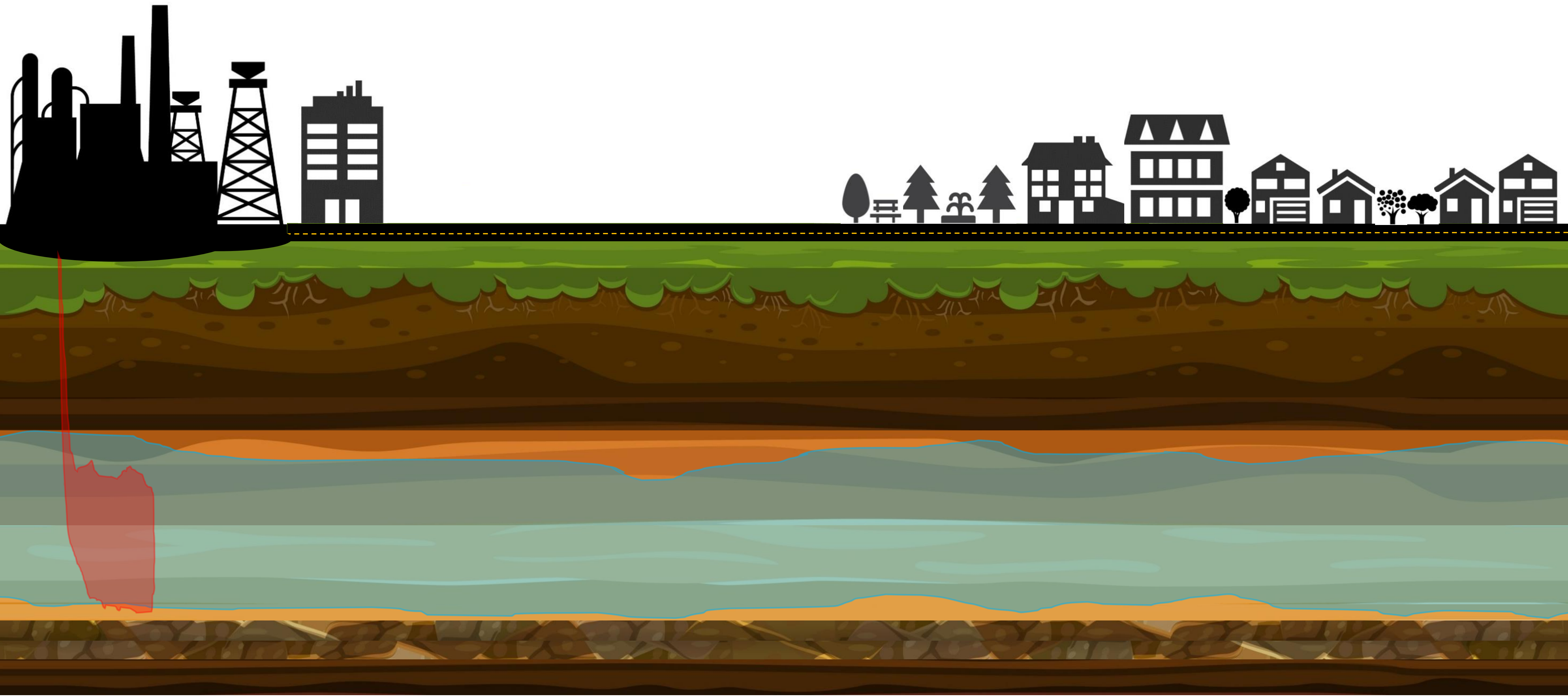
2. Concentration gradient driven **diffusion** governs transport in low permeability, **perched formations**



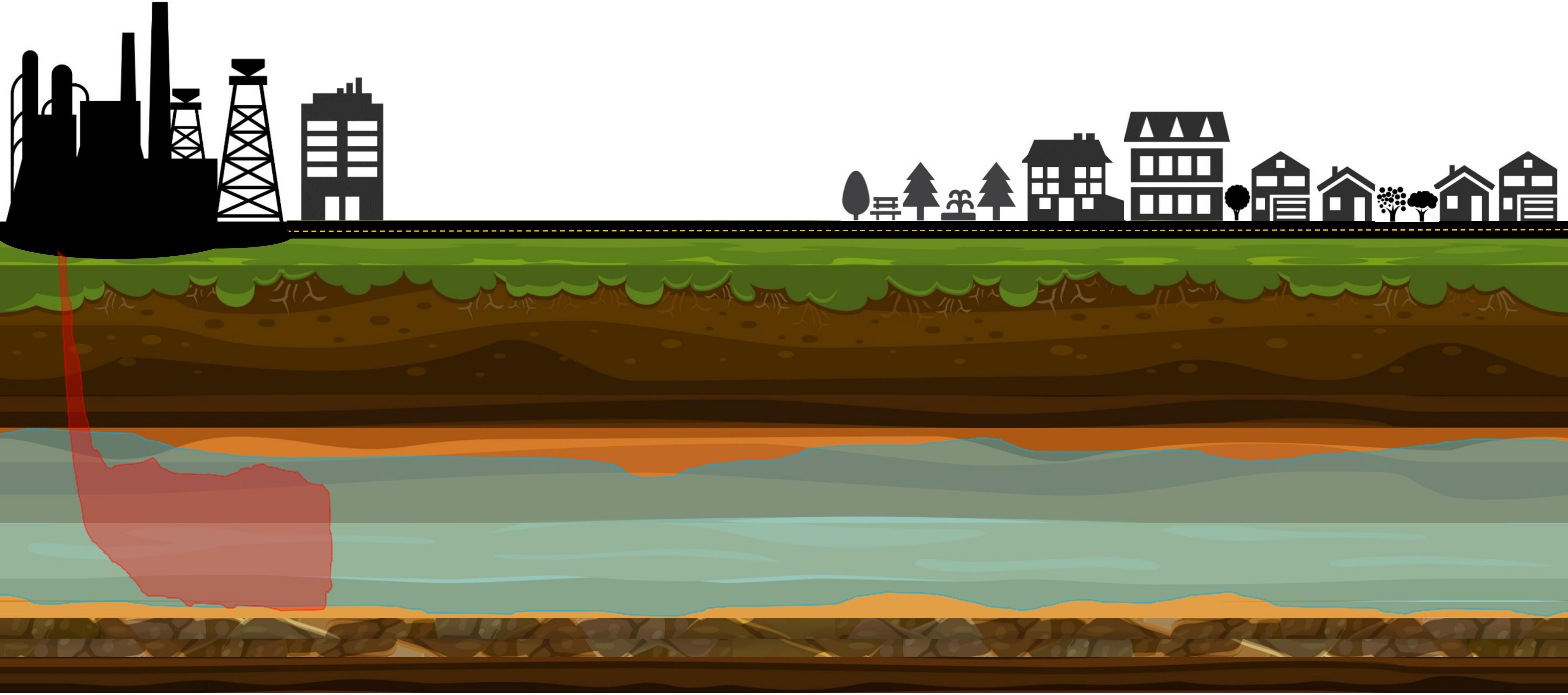
Transport Kinetics



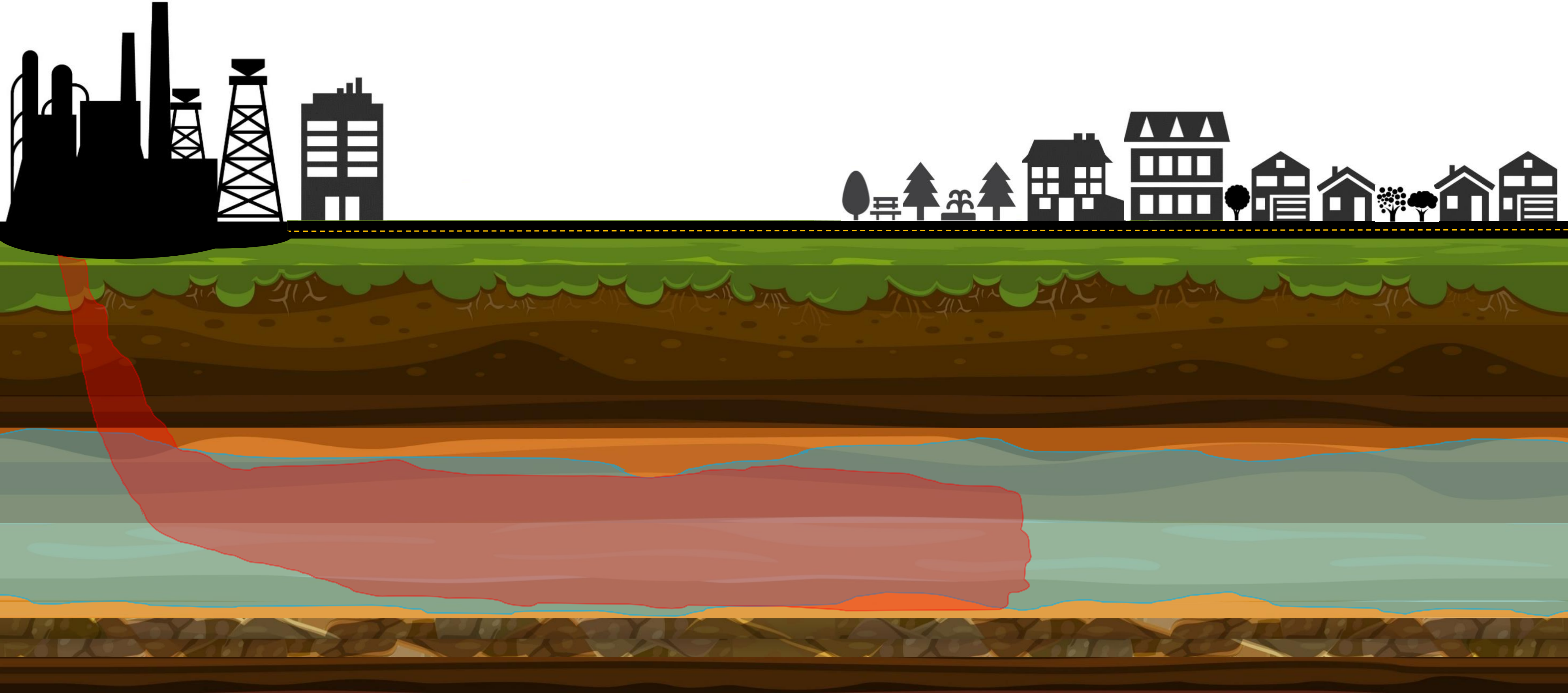
Groundwater contamination



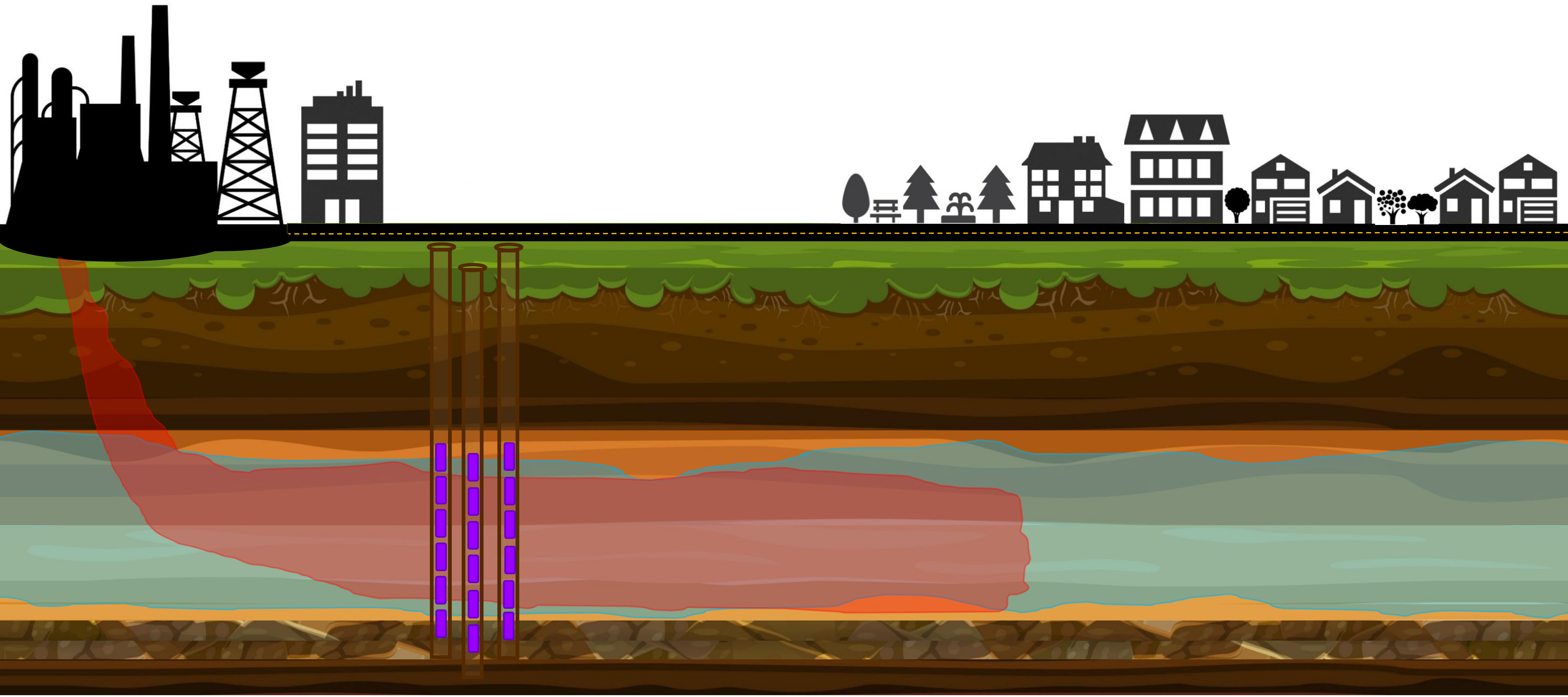
Plume migration



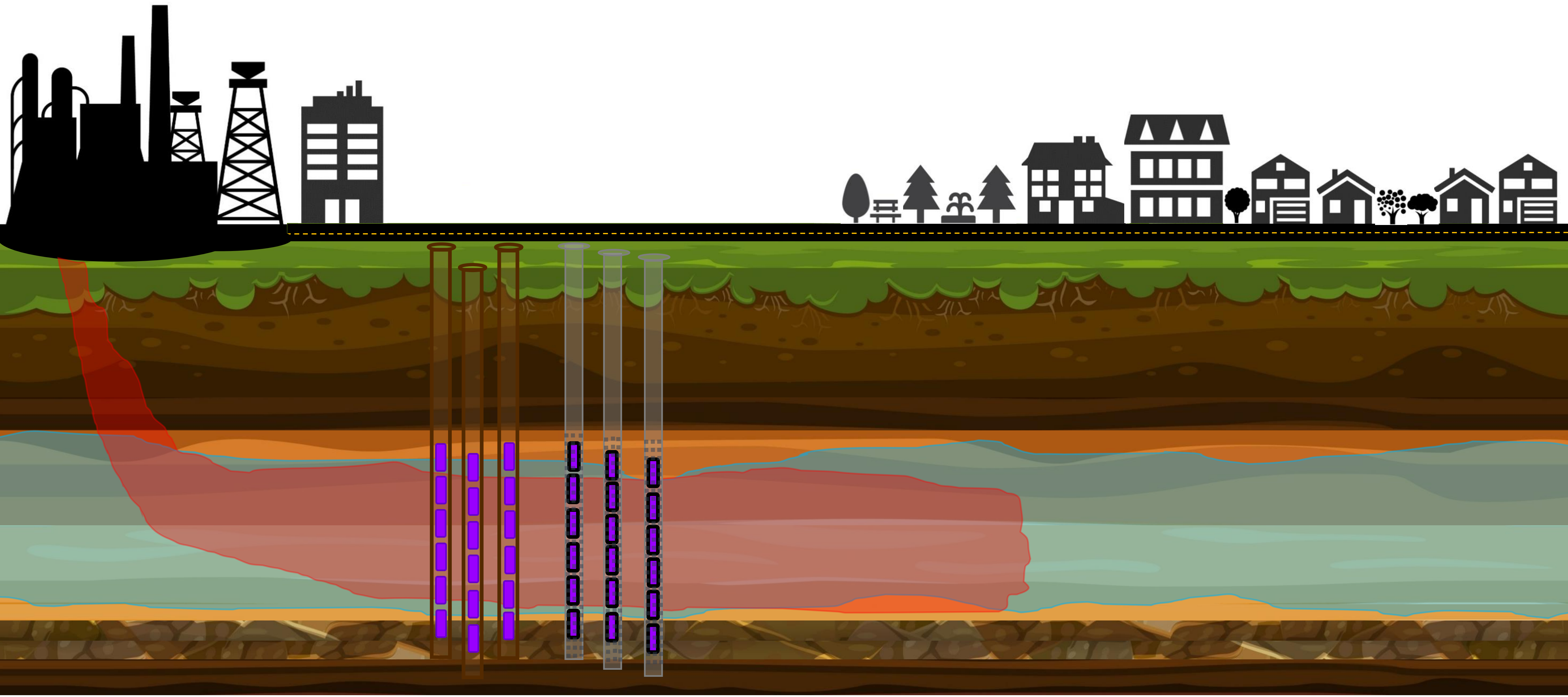
Further plume migration



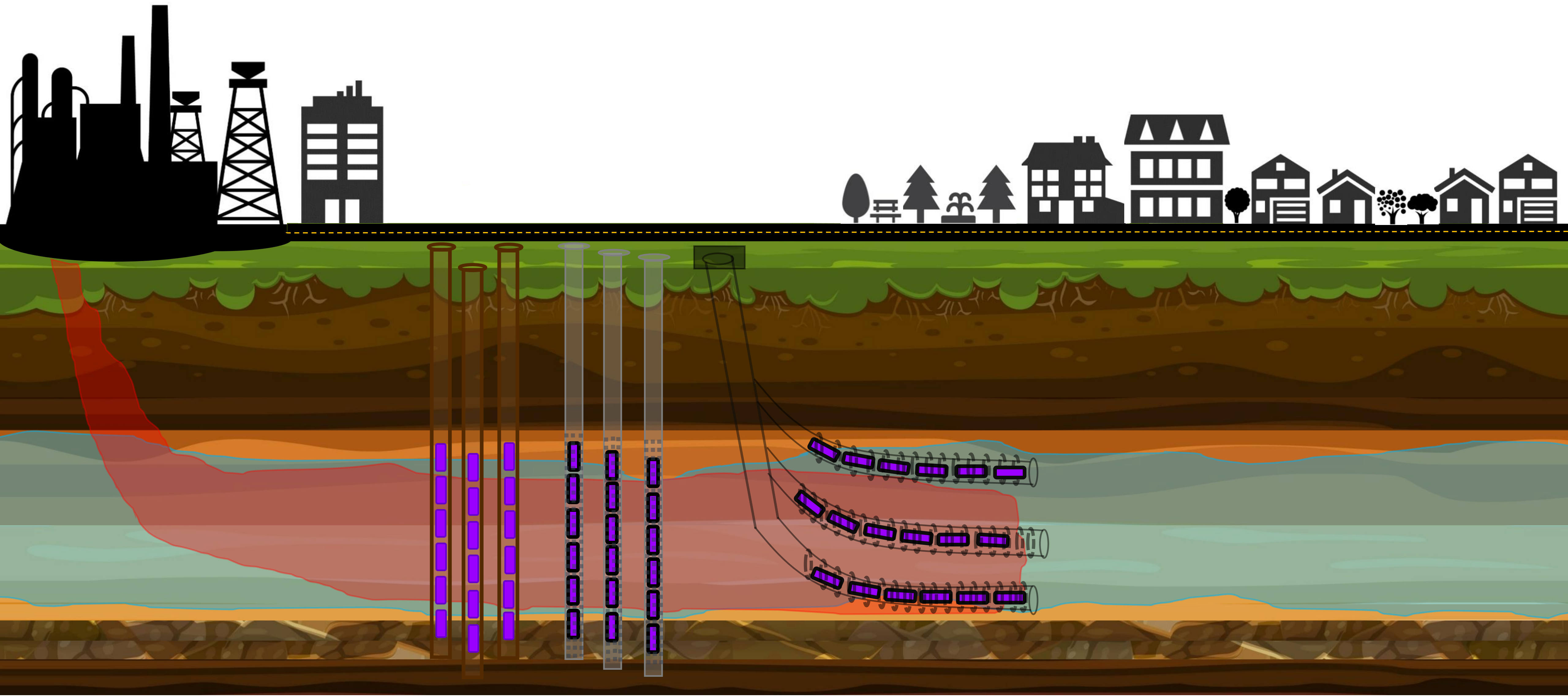
…….and further



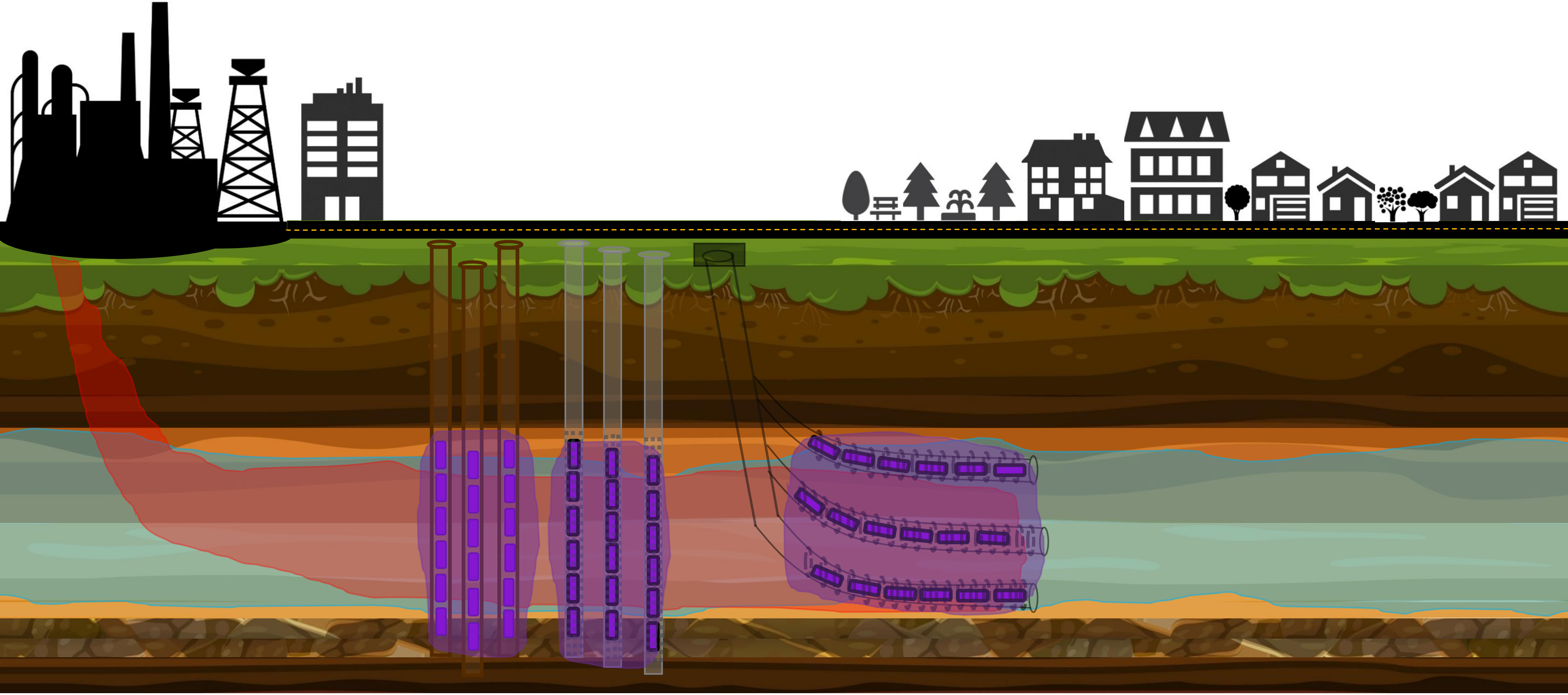
SOCORE – borehole/DPT/auger installation



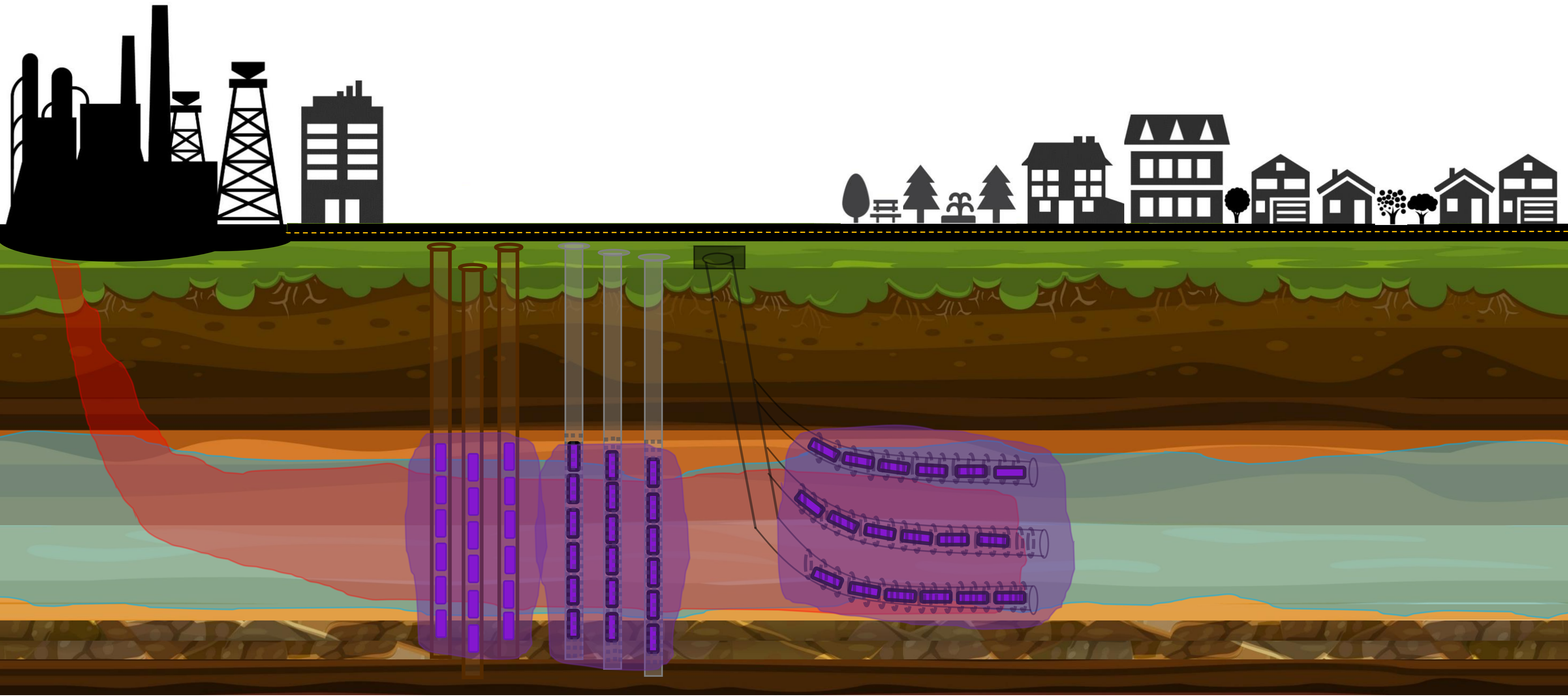
SOCORE – well installation



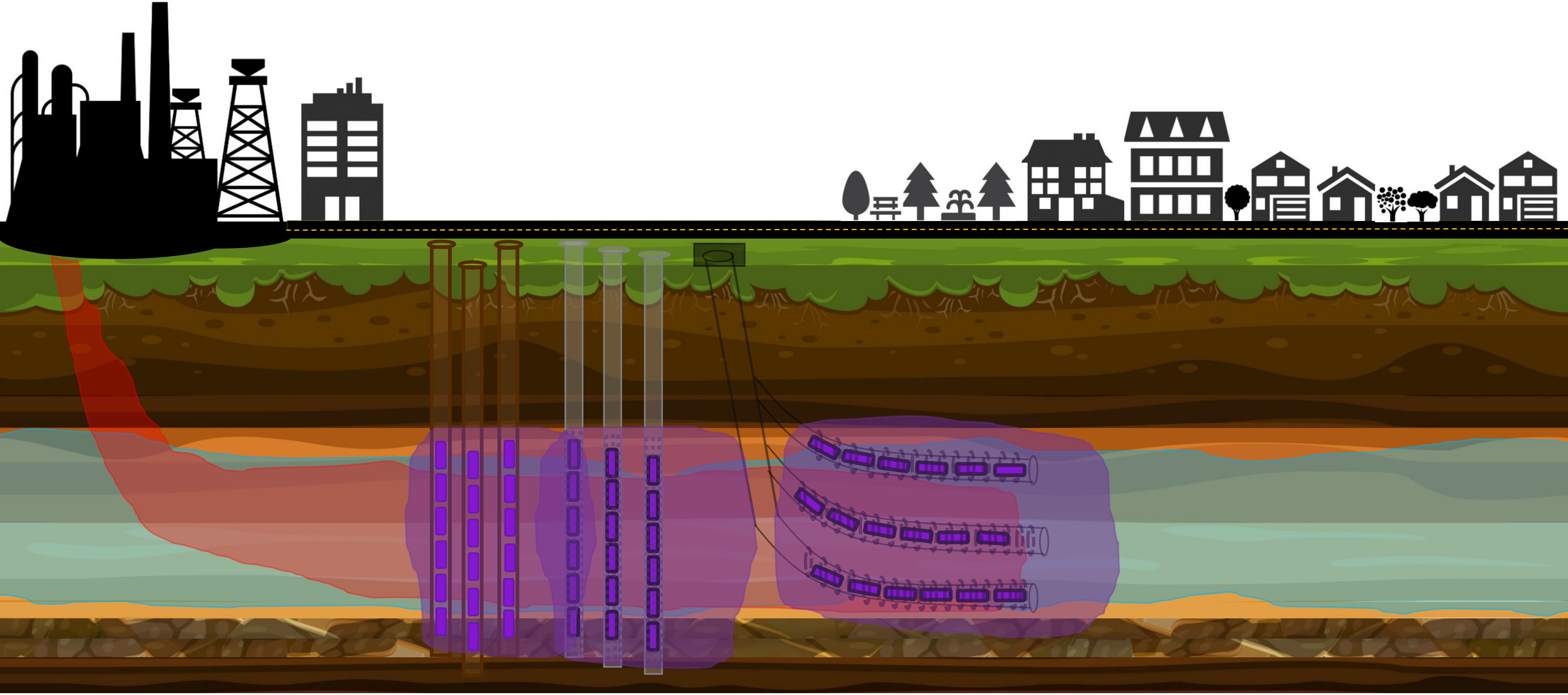
SOCORE – horizontal well/DD-PRB installation



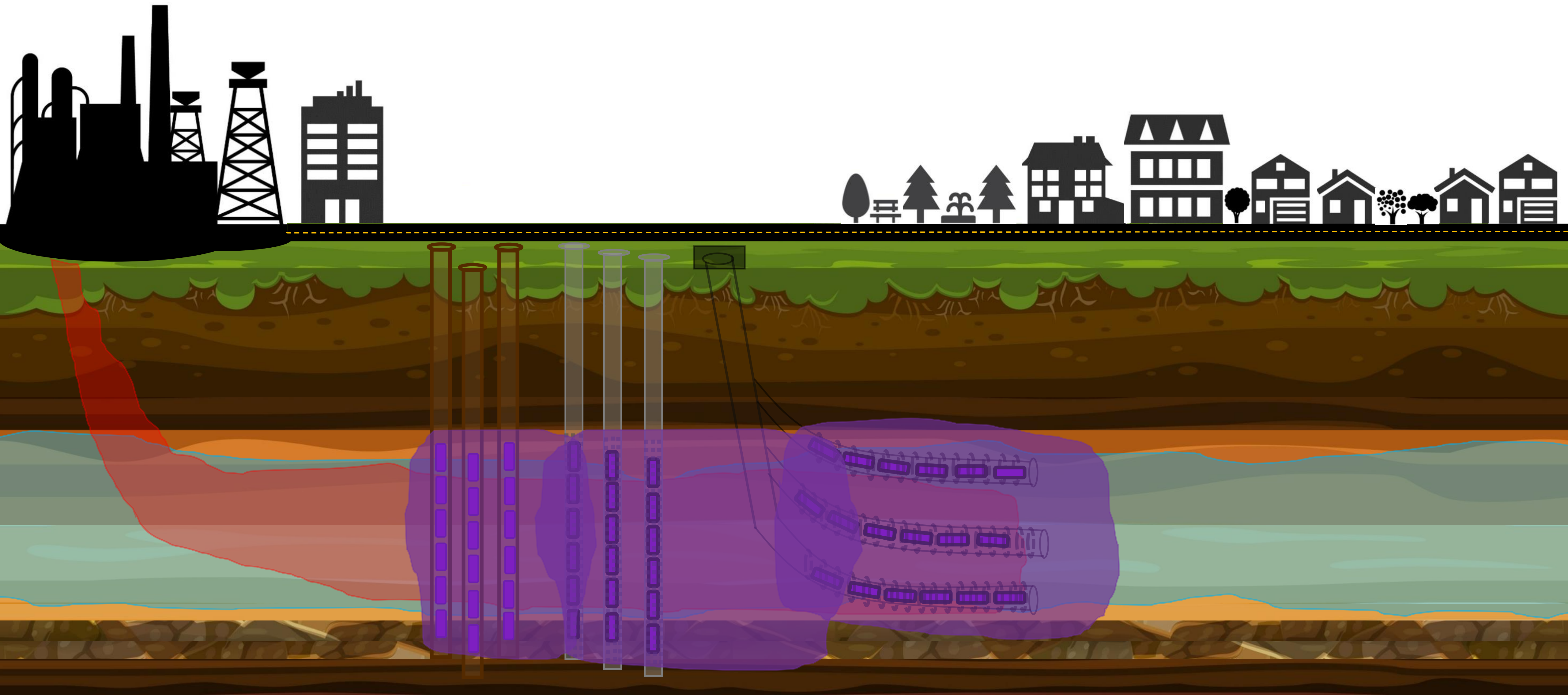
SOCORE – reactant release and distribution



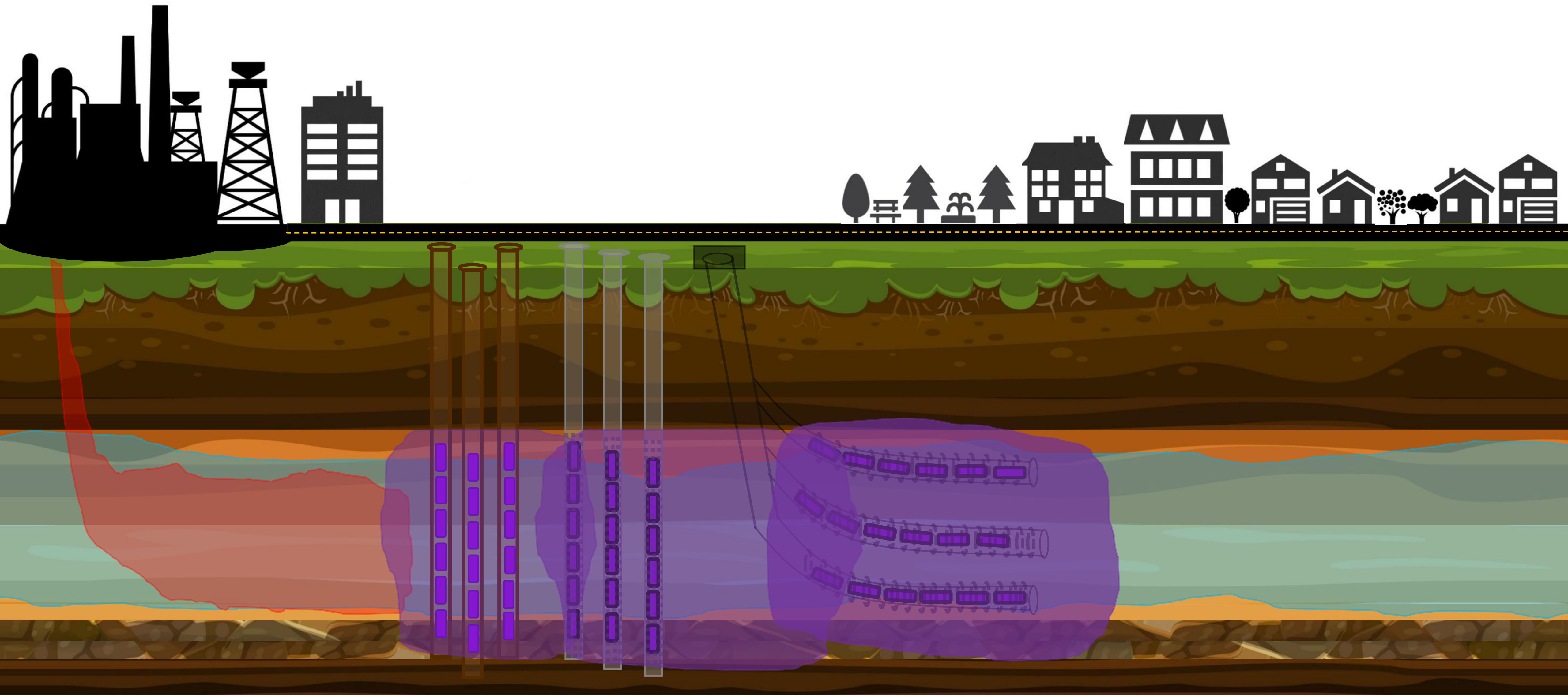
SOCORE – reactant release and distribution continued



SOCORE – reactant release and distribution continued….



SOCORE – reactive zone established



Plume reduction/interception

Site Selection – When and where is SOCORE an appropriate remedial approach?

- Reactive Treatment/Interceptor Zones
- Saturated Conditions (**<u>not</u>** a vadose zone technology)
- Active facilities **<u>or</u>** remote locations where minimal remedial infrastructure is desired
- Heterogeneous formations and LPM where back diffusion would otherwise be problematic in a liquid application
- Remember stoichiometry – **<u>don't under-dose the application</u>....**there is no magical chemistry

CASE STUDY #1

(New Jersey)

Background:

Low-Cost, Low-Maintenance, and Green Reactive Treatment Zone

COC's - **PCE**, TCE, DCE, VC in GW (100,000+ug/L total targeted CVOC in GW at source zone target well)

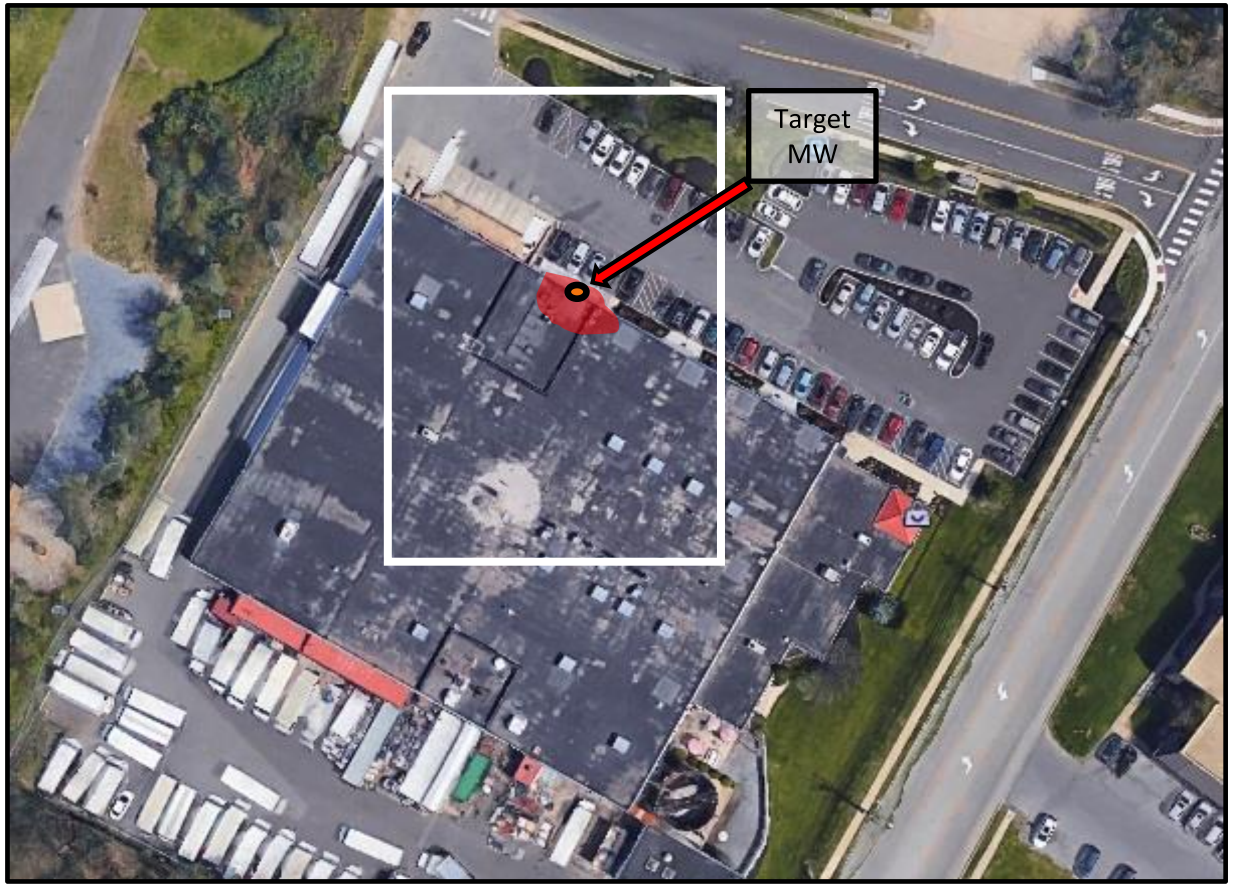
Geology - impacted fill to 10-12' bgs, underlain by LPM clay formation

Site logistics:

- Active industrial facility
- Remaining source zone soils are located at **building foundation** and adjacent to **sewer utilities**
- Source remains in place

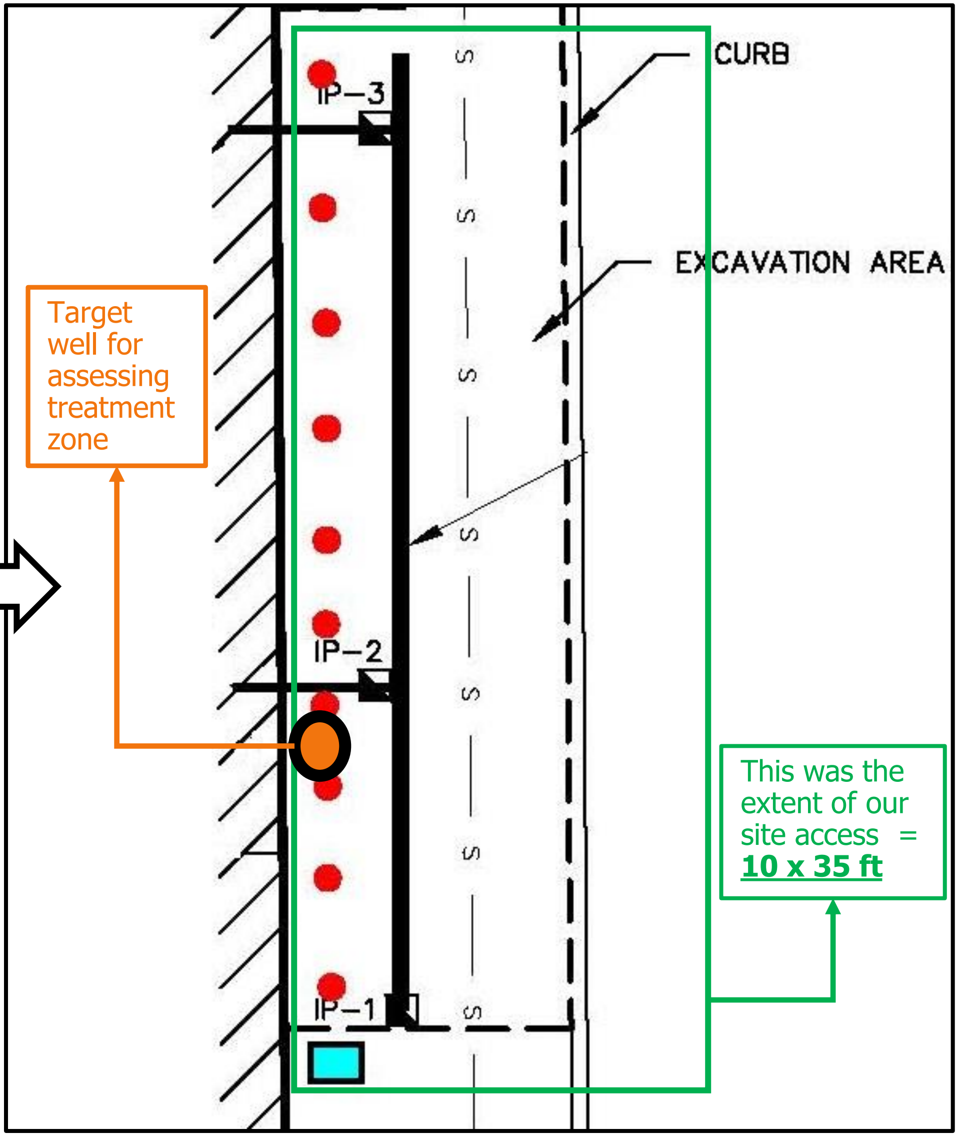
Previous remediation activities - extensive Free Product Recovery activities and limited source excavation, 2 RegenOx injections

Client's goals - seeking cost-effective and low-impact remedial strategy to address source area groundwater



Background:

Low-Cost, Low-Maintenance, and Green Reactive Treatment Zone

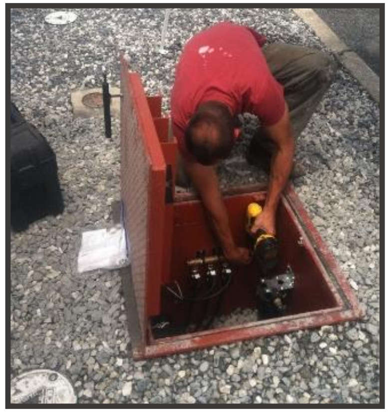


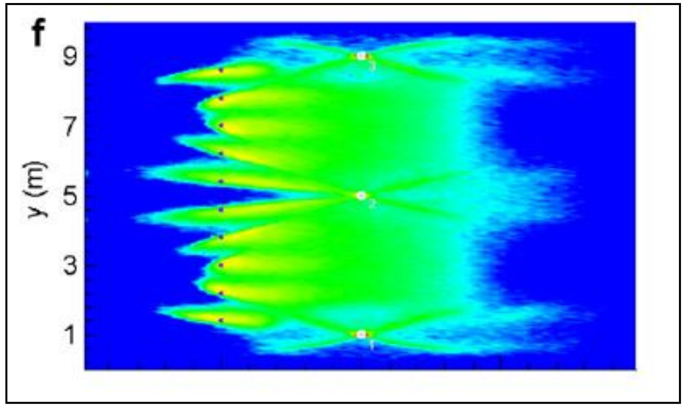
Remedial Approach:

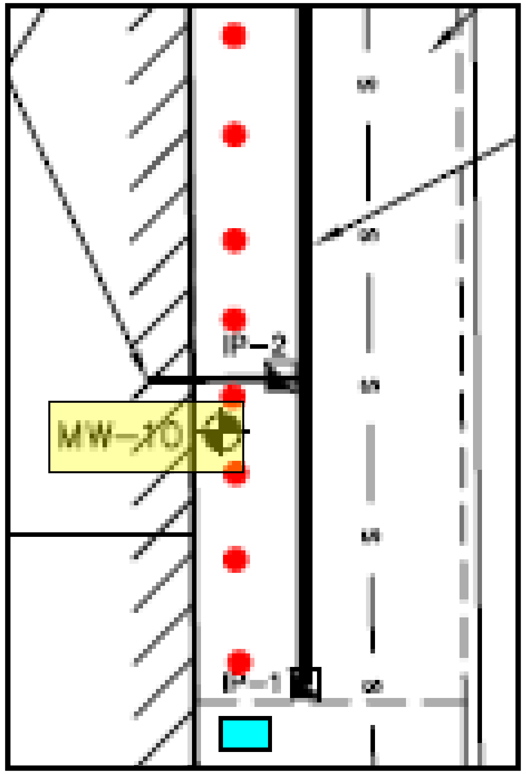
3-Step Implementation

1) Injection

- 10 DPT boreholes
- Top down injection from 4′-10′ bgs
- 40 gal of 10% NaMnO4 per borehole from 4′-10′ bgs
- followed by 25 gallon chase injections of clean water to assist distribution
- DPT boreholes placed on **3-foot spacings in a single row**







2) SOCORE –

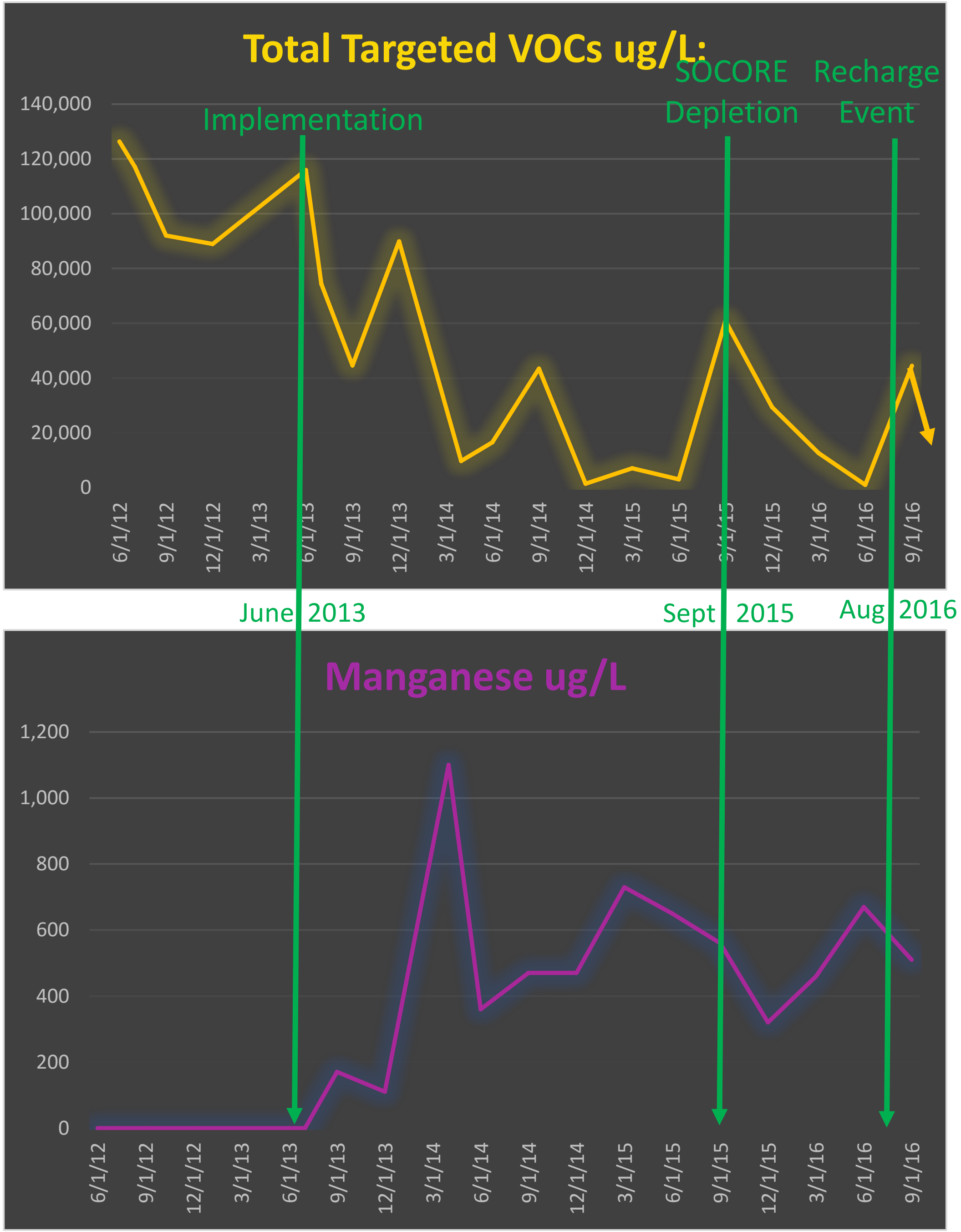
- each borehole completed with 2″ ID PVC piezometer
- screened from 2′-12″ bgs (target interval)
- 4 SOCORE Permanganate cylinders with holders were deployed from 2′ -12′ bgs at each
- Total of 40 SOCORE Permanganate cylinders (1.35″ x 24″)

3) Recirculation –

- To accelerate KMnO4 mixing/distribution across the reactive interceptor zone
- low-flow solar-powered recirculation system was also installed
- including: piston pump, manifolds, solenoid valves, programmable timer, and re-circulation lines.

Results:

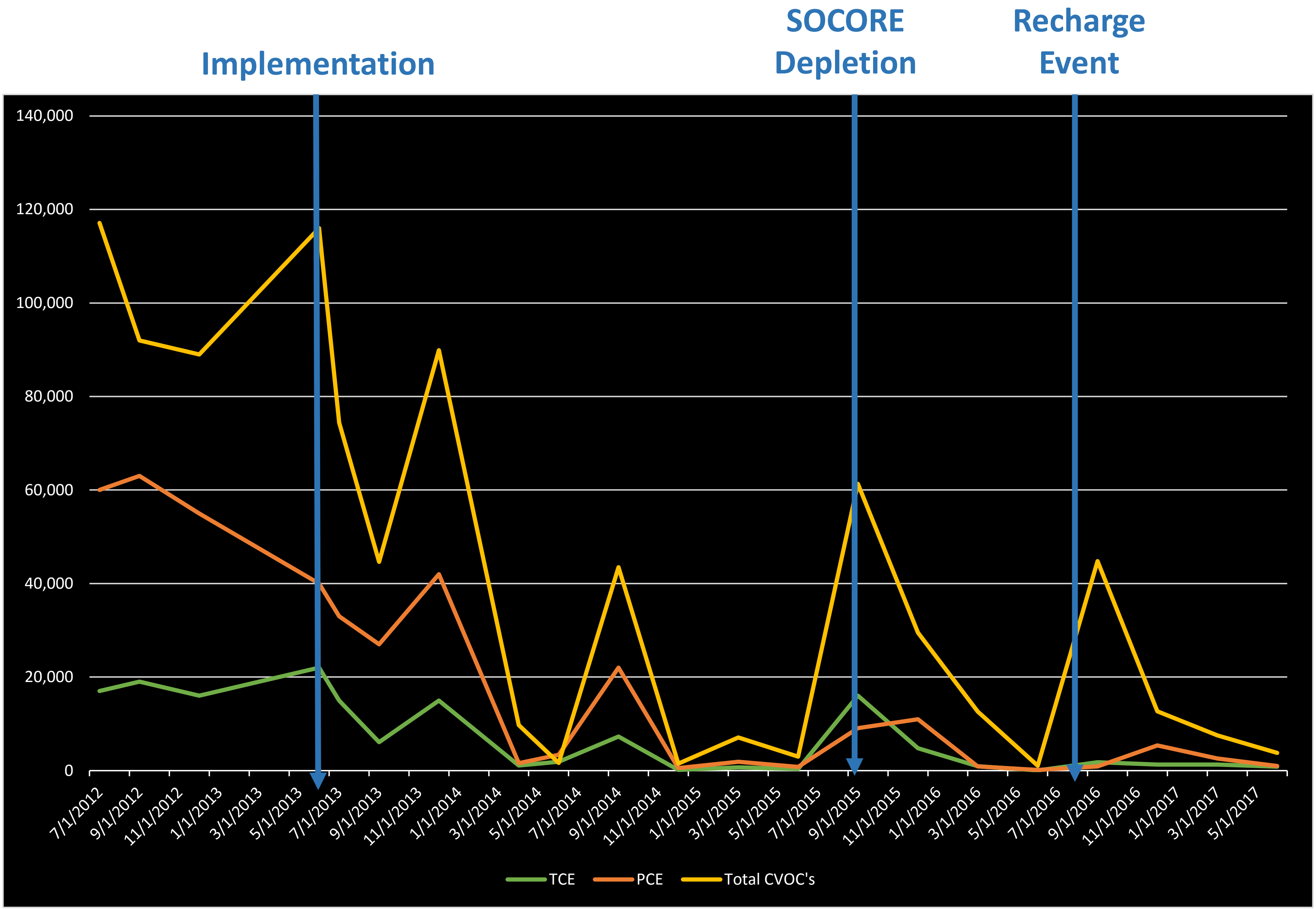
Low-Cost, Low-Maintenance and, Green Reactive Interceptor Zone



- The system was installed in June 2013 at a cost of **<u>less than $75,000</u>**.
- VOC concentrations decreased at target monitoring well as expected
- 2.5 years after remedial implementation:
  - rising VOC concentrations
  - decreasing Mn concentrations
  - SOCORE Permanganate re-charge event was due
- The first SOCORE material **<u>re-charge event was performed in August 2016 for less than $10,000</u>**.

Results:

Updated GWM Data



CASE STUDY #2

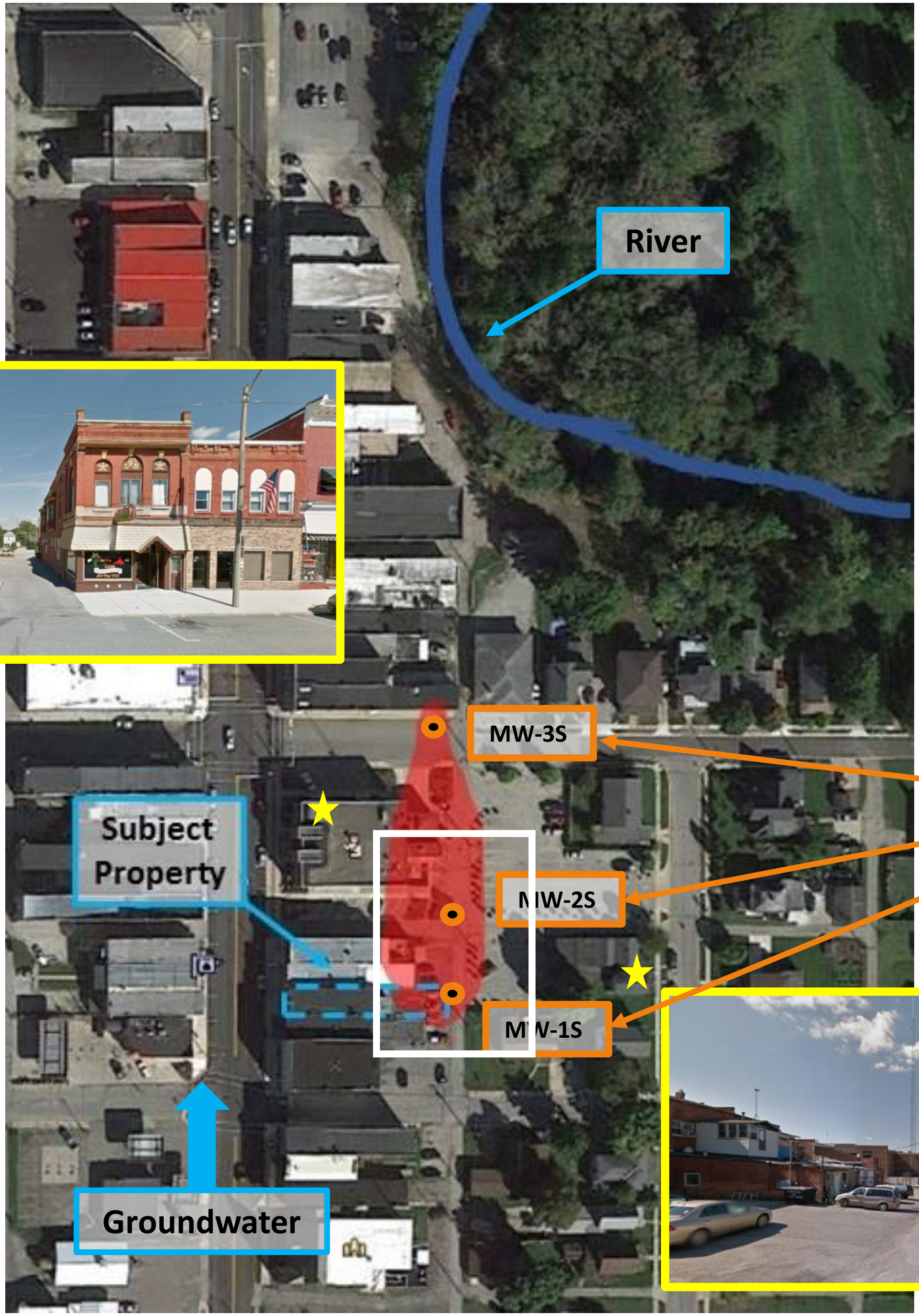
(Indiana)

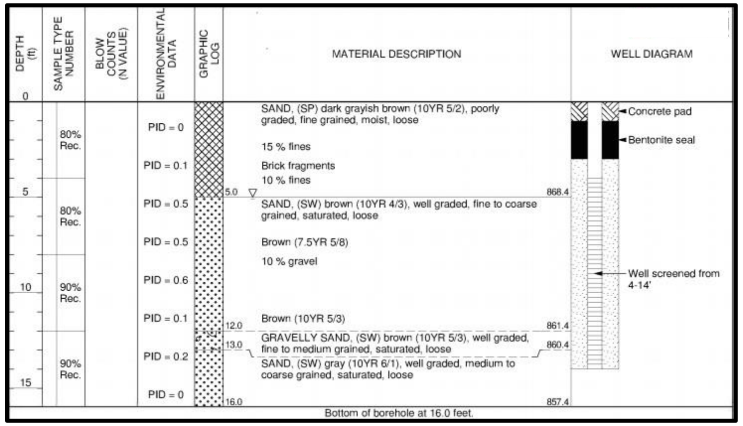
Background:

Reactive Treatment Zone & Interceptor Zone

- COC's - **PCE**, TCE, VC (**100-500 ug/L Total CVOC** concentration in GW)
- Geology - fill and sandy loam to 5′ bgs, underlain by transmissive sands and gravelly sands
- Site logistics:
  - Remaining source zone soils are located behind building adjacent to **sewer utilities** and an alleyway
  - Neighboring properties include restaurants, retail store, City Hall and multiple **residences**
- Previous remediation activities – Shallow source zone soils excavation & **SVE/AS** mechanical remediation
- Client's goals – mitigate off-site migration of CVOC GW plume

Site Layout





Primarily Sands

	Screen	PCE	TCE	VC
MW-3S	6-16 ft	27.2	11	ND
MW-2S	5-15 ft	215	5.3	ND
MW-1S	6-16 ft	403	6.3	ND

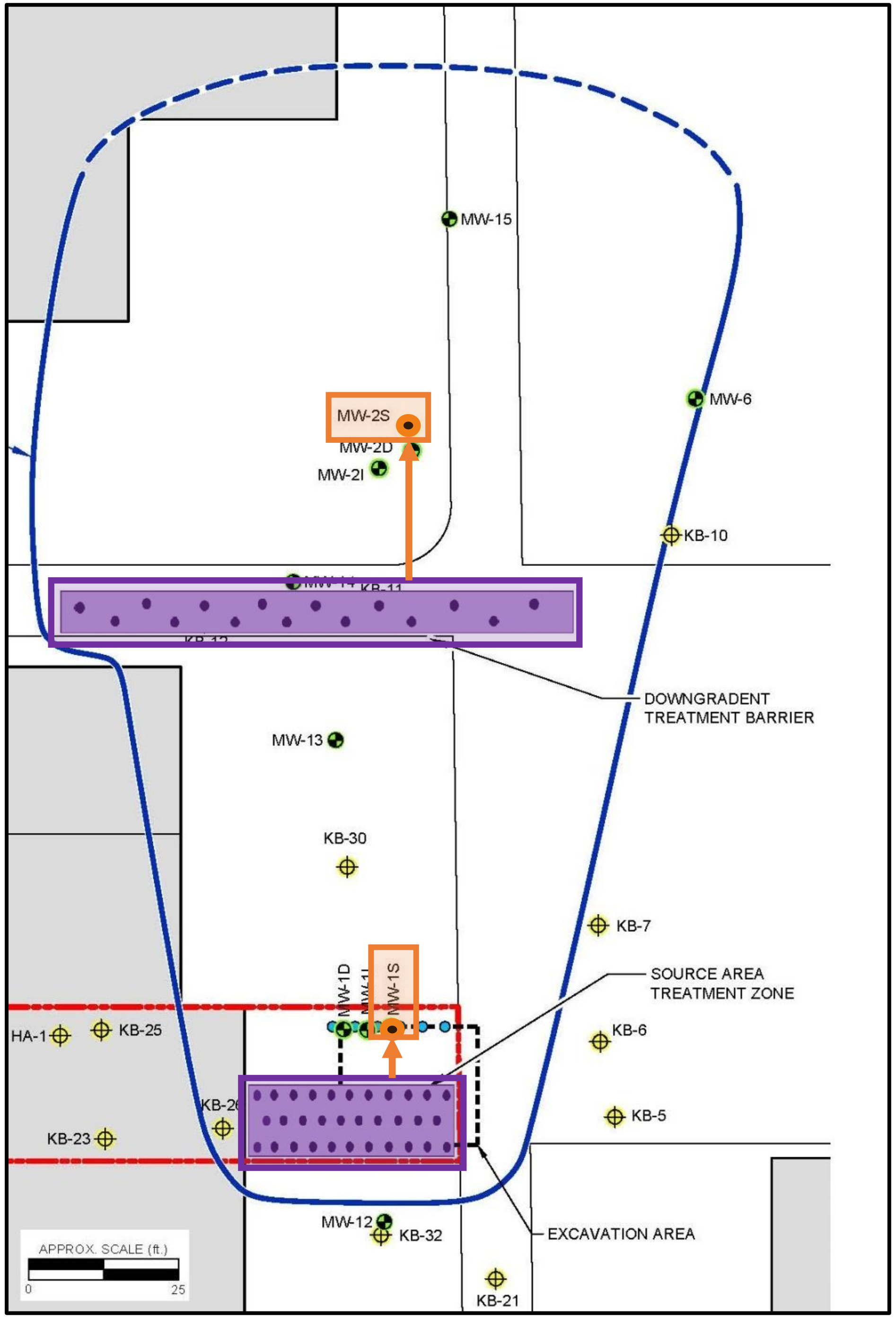
Site Layout: SOCORE Permanganate Reactive Zones

2 - Downgradient Treatment Interceptor:

- 90’ wide x 10’ deep - installation area
- (15) 3.25” DPT boreholes to 16’ bgs
- 4 cylinders per borehole (8’ – 16’ bgs target interval)
- 2 rows, wider spacing than source area
- 60 SOCORE cylinders - 2.5” x 24” SOCORE Permanganate Cylinders
- Approx. 25 ft up-gradient from target well **MW-2S**

1 - Source Area Treatment Zone:

- 45’ wide x 15’ deep - installation area
- (35) 3.25” DPT boreholes to 16’ bgs
- 3 cylinders per borehole (10’ – 16’ bgs target interval)
- 3 rows
- 105 SOCORE cylinders - 2.5” x 24” SOCORE Permanganate Cylinders
- Approx. 10 ft up-gradient from target well **MW-1S**



Site Photos

SOCORE Cylinders –
out of packaging

Preparing cylinders for
deployment down DPT
tooling

Geoprobe 6620 DPT - 50
boreholes to 16 fbgs

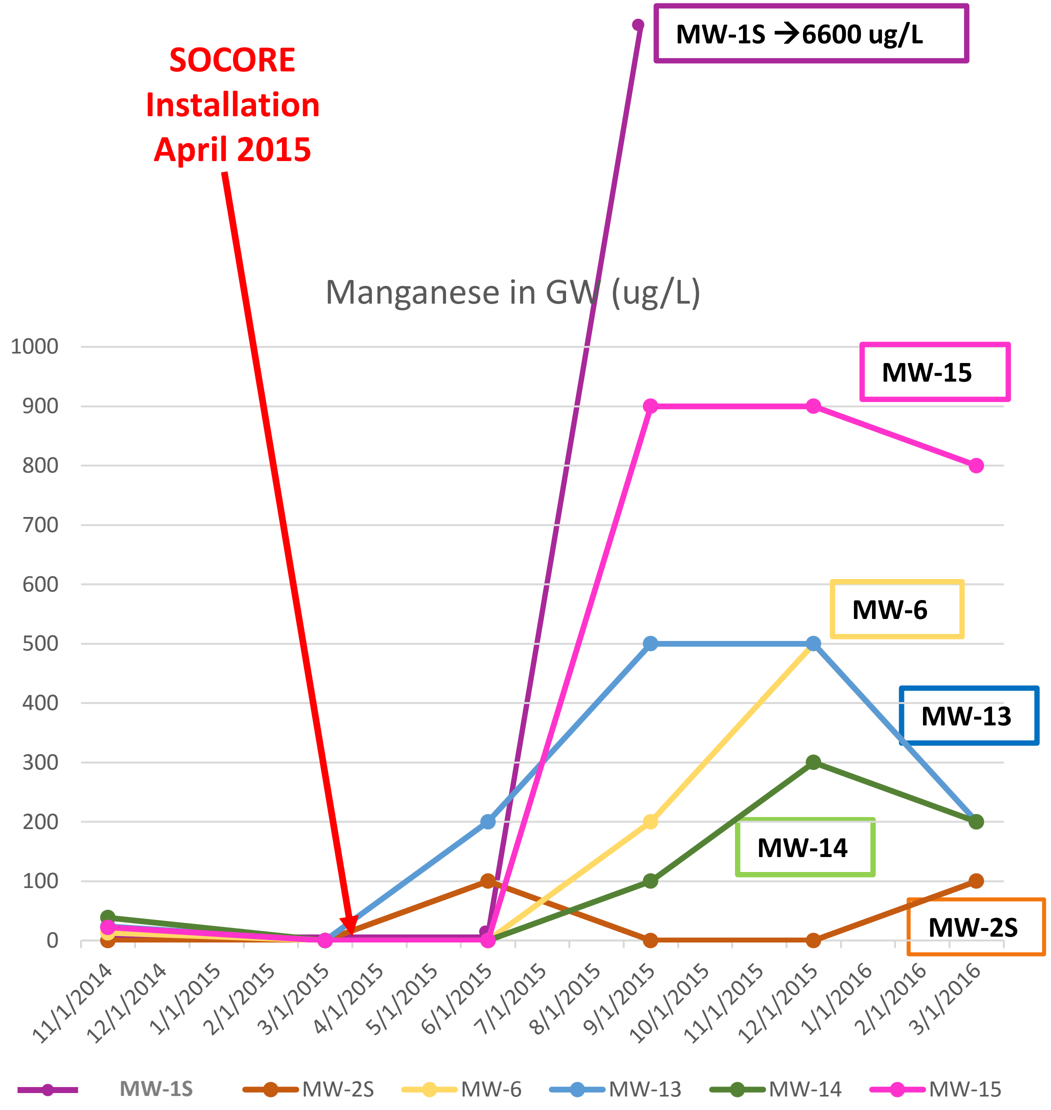
Site Photos Continued

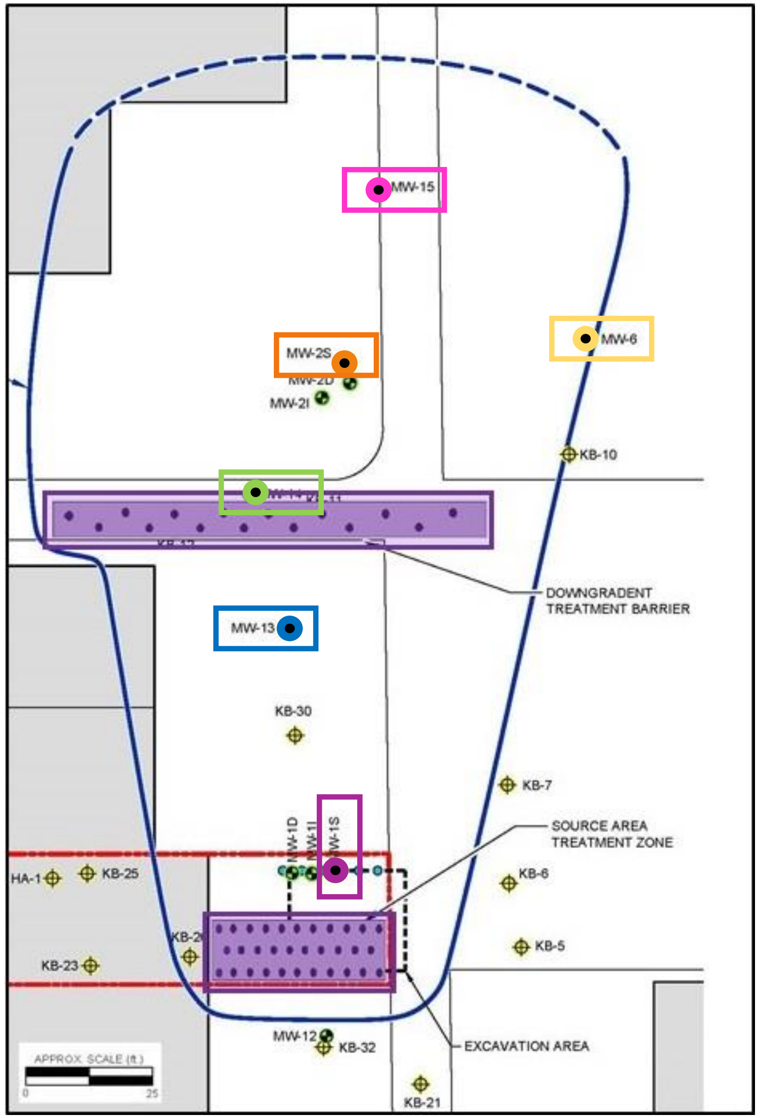
On-site SOCORE soil borings with nearby SVE manhole.

Downgradient SOCORE soil borings

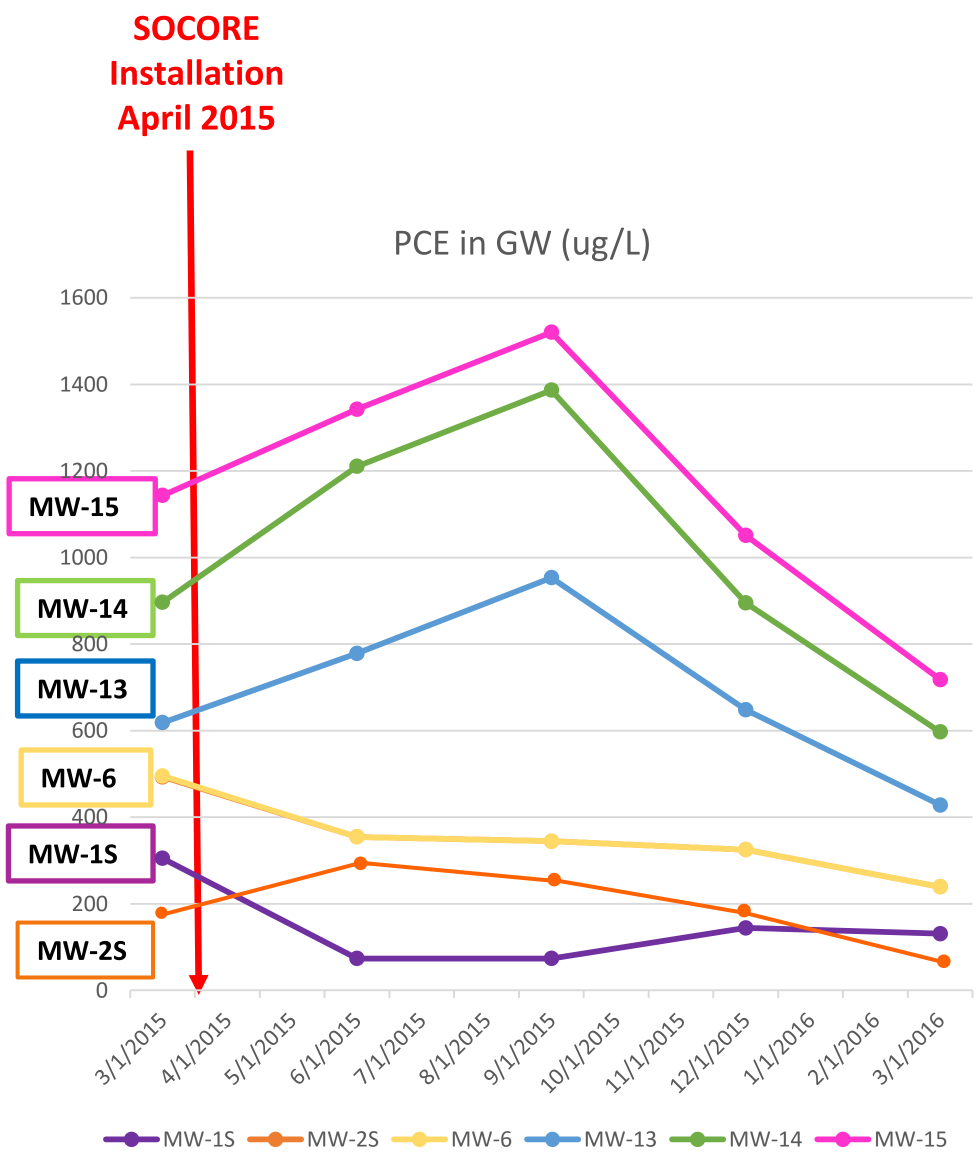
Results:

MANGANESE





Results: PCE



SOCORE
Installation
April 2015
PCE in GW (ug/L)
1600
1400
1200
1000
800
600
400
200
0
MW-15
MW-14
MW-13
MW-6
MW-1S
MW-2S
3/1/2015
4/1/2015
5/1/2015
6/1/2015
7/1/2015
8/1/2015
9/1/2015
10/1/2015
11/1/2015
12/1/2015
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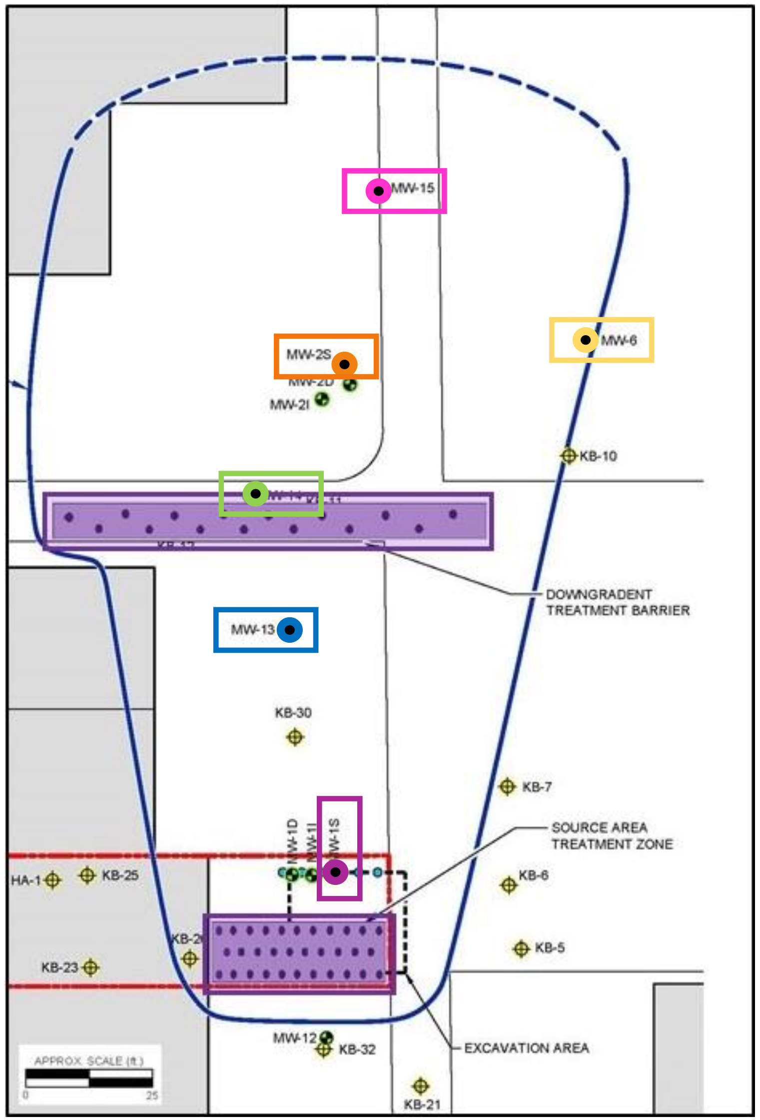
2/1/2016
3/1/2016
MW-1S
MW-2S
MW-6
MW-13
MW-14
MW-15



MW-15
MW-6
MW-2S
MW-2I
KB-10
DOWNGRADENT
TREATMENT BARRIER
MW-13
KB-30
KB-7
SOURCE AREA
TREATMENT ZONE
HA-1
KB-25
KB-6
KB-23
KB-5
MW-12
KB-32
EXCAVATION AREA
KB-21
APPROX. SCALE (ft.)

Cost and Time to Completion

TOTAL COST:

$80,000
(materials & labor)

TIME TO COMPLETION:

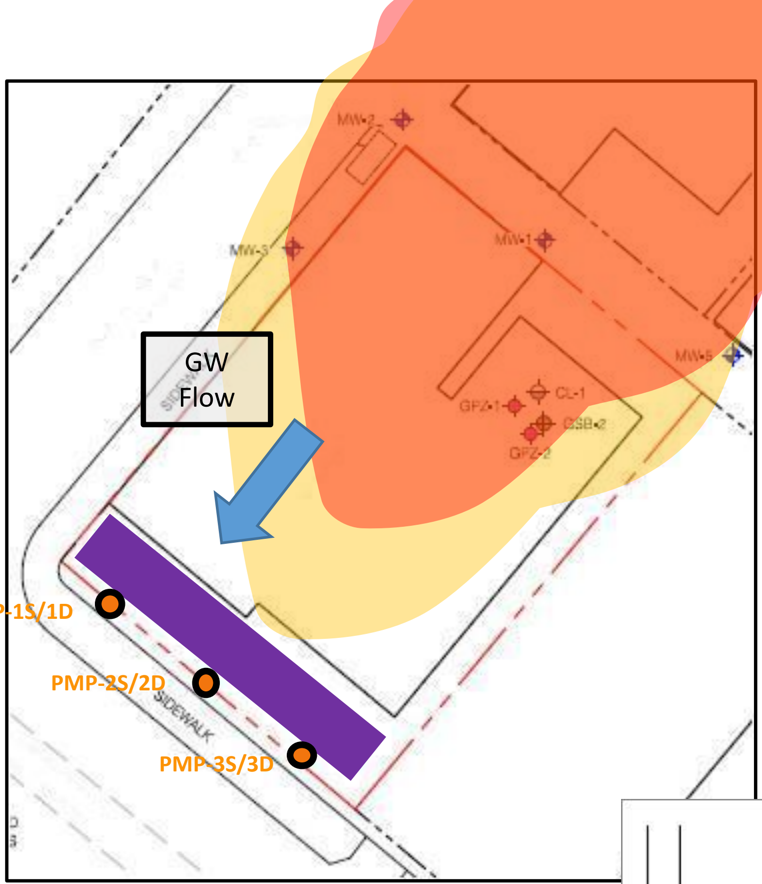
4 days

CASE STUDY #3

(California)

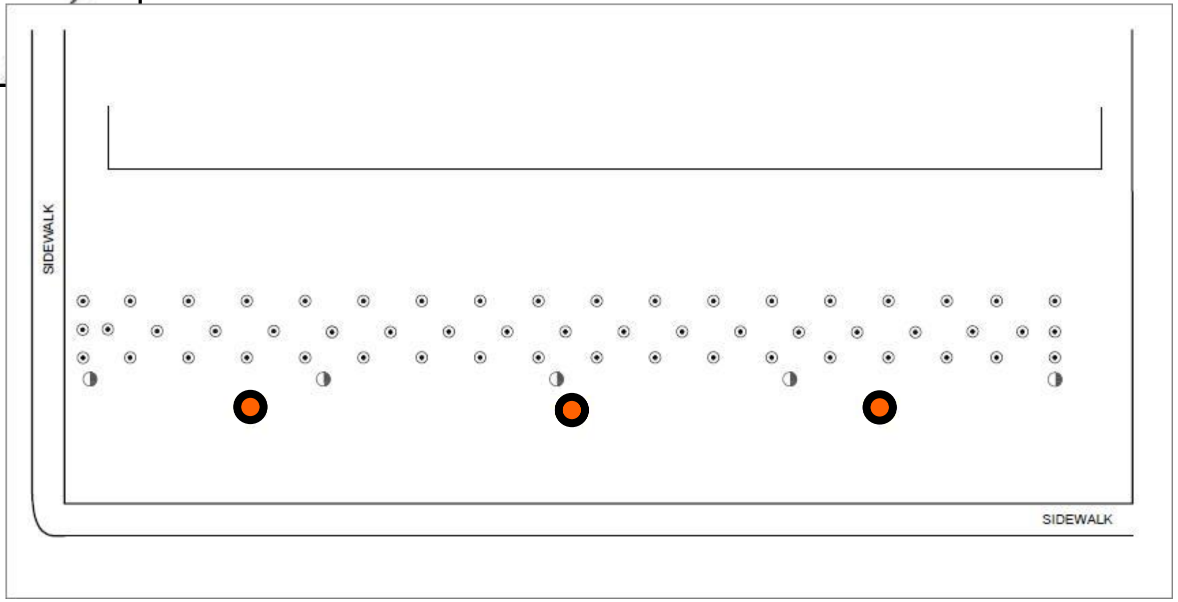
Background:

Reactive Interceptor Zone



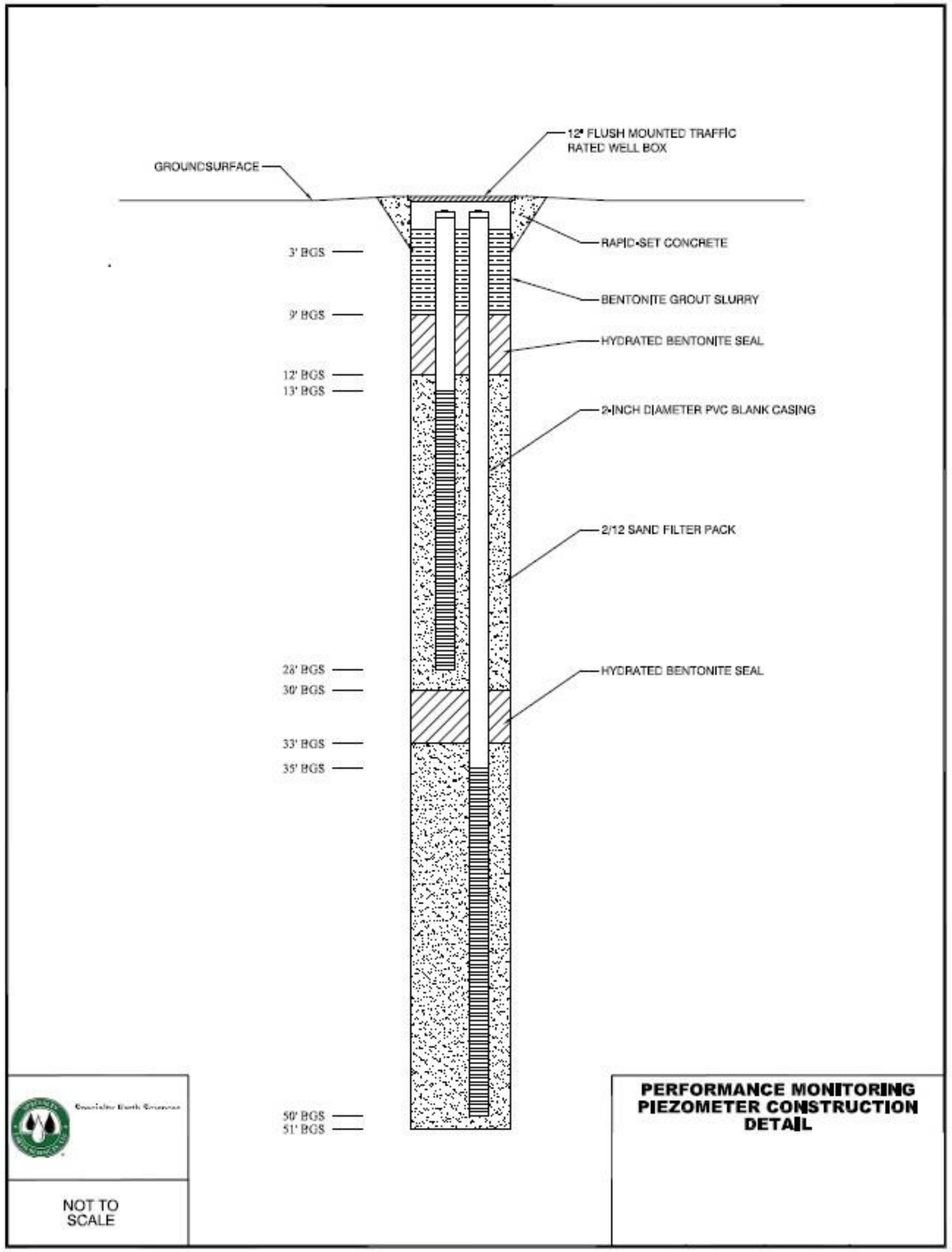
- <u>Geology</u> – stratified layers of bay muds and silty sands to 35′ bgs, underlain by sands and silty sands
    - Impacted interval - 10′-40′ bgs
- <u>COC</u> – CVOC's in GW migrating from up-gradient source (primarily PCE)
    - 10,000 ug/L baseline at PMP's
- Goal – mitigate further down-gradient plume migration

- 51 boreholes –
    1. Top down permanganate injection
    2. completed with 2″ piezometers for SOCORE deployment (459 total - 1.35″ x 24″ SOCORE Permanganate Cylinders)
- 3 (dual-nested) performance monitoring piezometers (PMP's)
- 5 permanganate obs piezometers (POP's)



Schematics:

PMP's

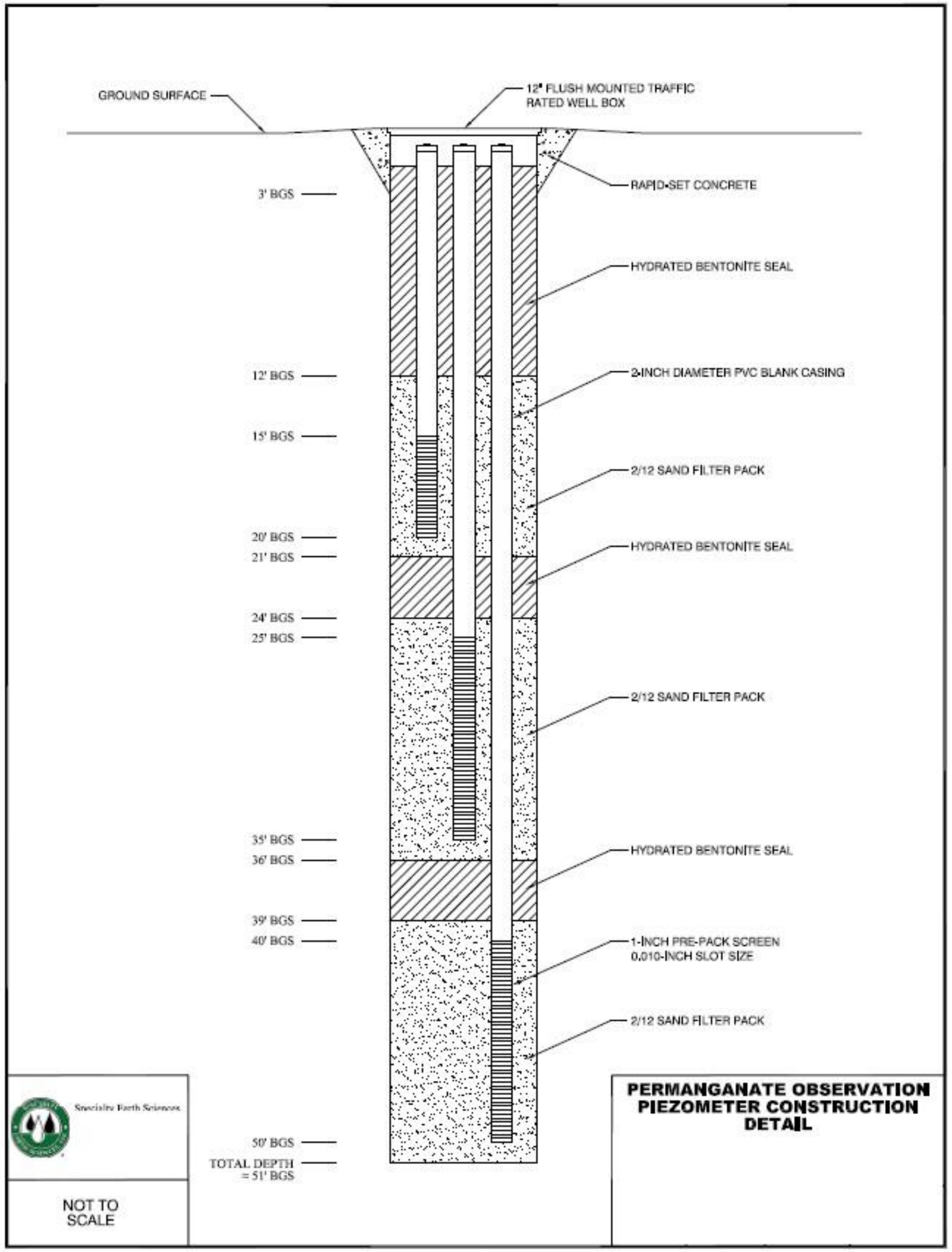


3 dual nested performance monitoring piezometers (PMP's):

- 15 feet of screen per piezometer
- Shallow & Deep Zones

Schematics:

POP's

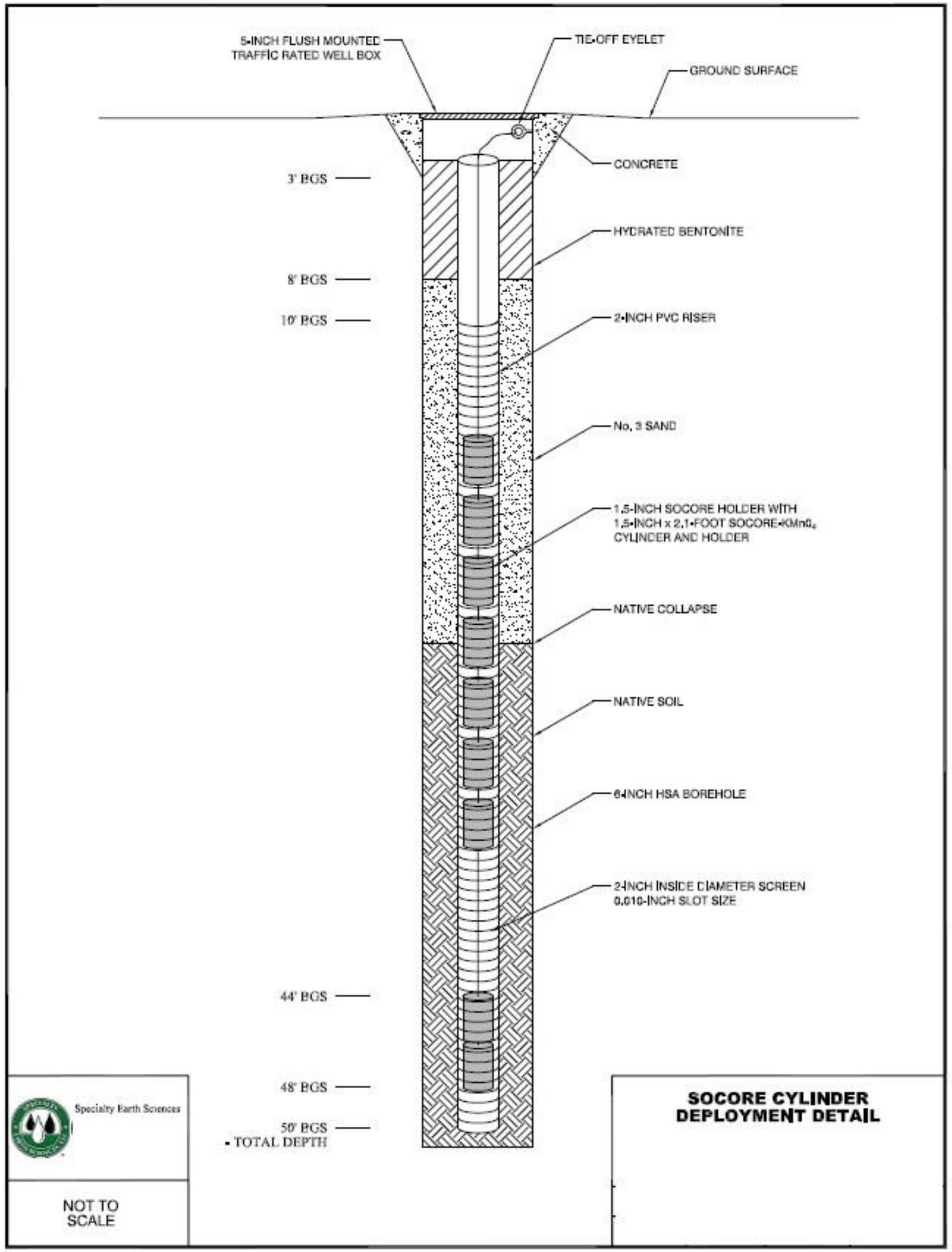


5 triple nested permanganate observation piezometers (POP's):

- 5-10 feet of screen per piezometer
- Shallow, Moderate, & Deep Zones

Schematics:

SOCORE deployment



51 SOCORE deployment wells:

- 40 feet of screen per well
- 9 SOCORE holders and cylinders per well

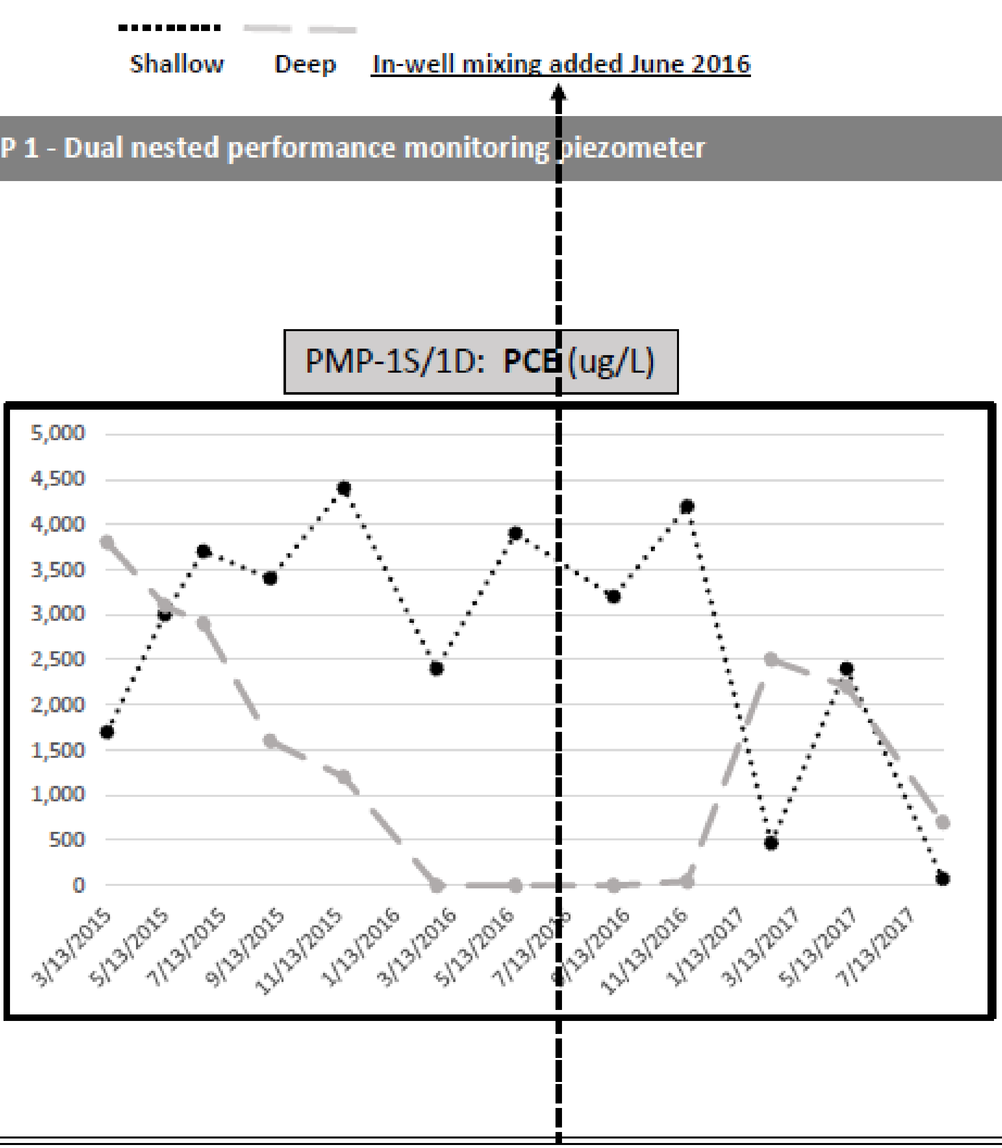
Site Photos:

Site Photos:

PCE Monitoring Data: PMP 1

PCE in Groundwater - PMP's

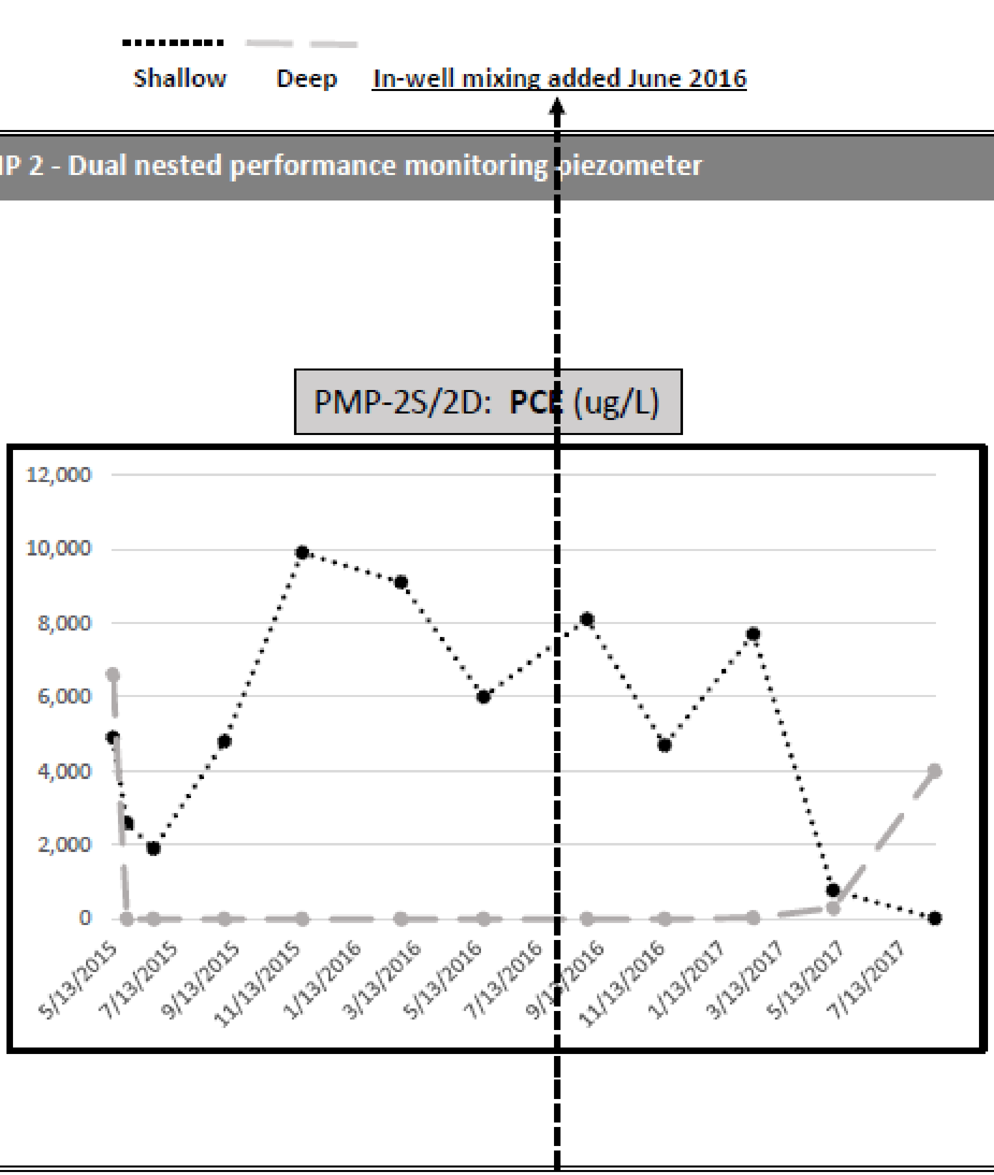
Sample ID	Date Sampled	PCE (µg/L)
PMP 1 - Dual nested performance monitoring piezometer		
PMP-1S - screened 13'-28' bgs		
PMP-1S	3/13/2015	1,700
PMP-1S	5/13/2015	3,000
PMP-1S	6/23/2015	3,700
PMP-1S	9/02/2015	3,400
PMP-1S	11/19/2015	4,400
PMP-1S	2/25/2016	2,400
PMP-1S	5/19/2016	3,900
PMP-1S	8/31/2016	3,200
PMP-1S	11/17/2016	4,200
PMP-1S	2/14/2017	470
PMP-1S	5/05/2017	2,400
PMP-1S	8/15/2017	70
PMP-1D - screened 35' - 50' bgs		
PMP-1D	3/13/2015	3,800
PMP-1D	5/13/2015	3,100
PMP-1D	5/27/2015	2,900
PMP-1D	6/23/2015	1,600
PMP-1D	9/02/2015	1,200
PMP-1D	11/19/2015	ND<0.22
PMP-1D	2/26/2016	ND<1.0
PMP-1D	5/19/2016	ND<5.0
PMP-1D	8/30/2016	43
PMP-1D	11/17/2016	2,500
PMP-1D	2/14/2017	2,200
PMP-1D	5/05/2017	700
PMP-1D	8/15/2017	3,100



PCE Monitoring Data: PMP 2

PCE in Groundwater - PMP's

Sample ID	Date Sampled	PCE (µg/L)
PMP 2 - Dual nested performance monitoring piezometer		
PMP-2S - screened 13'-28' bgs		
PMP-2S	3/13/2015	4,900
PMP-2S	5/13/2015	2,600
PMP-2S	5/27/2015	1,900
PMP-2S	6/23/2015	4,800
PMP-2S	9/02/2015	9,900
PMP-2S	11/19/2015	9,100
PMP-2S	2/26/2016	6,000
PMP-2S	5/19/2016	8,100
PMP-2S	8/31/2016	4,700
PMP-2S	11/17/2016	7,700
PMP-2S	2/14/2017	780
PMP-2S	5/05/2017	17
PMP-2S	8/15/2017	5,100
PMP-2D - screened 35' - 50' bgs		
PMP-2D	3/13/2015	6600
PMP-2D	5/13/2015	4.0
PMP-2D	5/27/2015	3.5
PMP-2D	6/23/2015	1.7
PMP-2D	9/03/2015	ND<0.43
PMP-2D	11/19/2015	ND<0.43
PMP-2D	2/26/2016	ND<1.0
PMP-2D	5/19/2016	2.4
PMP-2D	8/30/2016	ND<1.0
PMP-2D	11/17/2016	35
PMP-2D	2/14/2017	300
PMP-2D	5/05/2017	4,000
PMP-2D	8/15/2017	77



PCE Monitoring Data: PMP 3

PCE in Groundwater - PMP's

Shallow   Deep   In-well mixing added June 2016

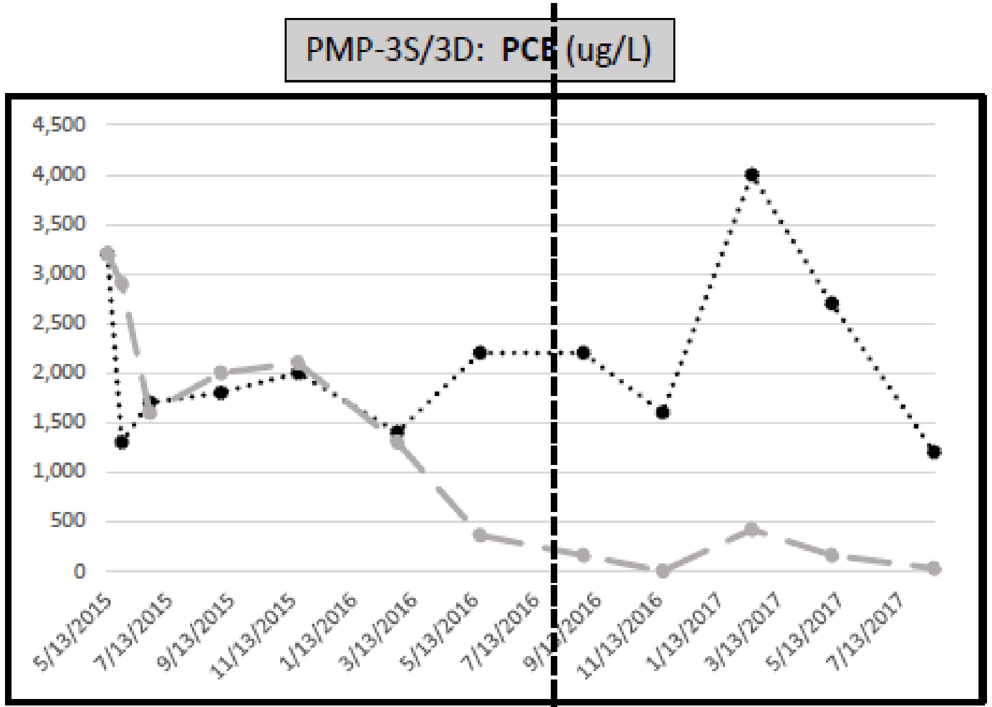
PMP 3 - Dual nested performance monitoring piezometer

PMP-3S - screened 13'-28' bgs

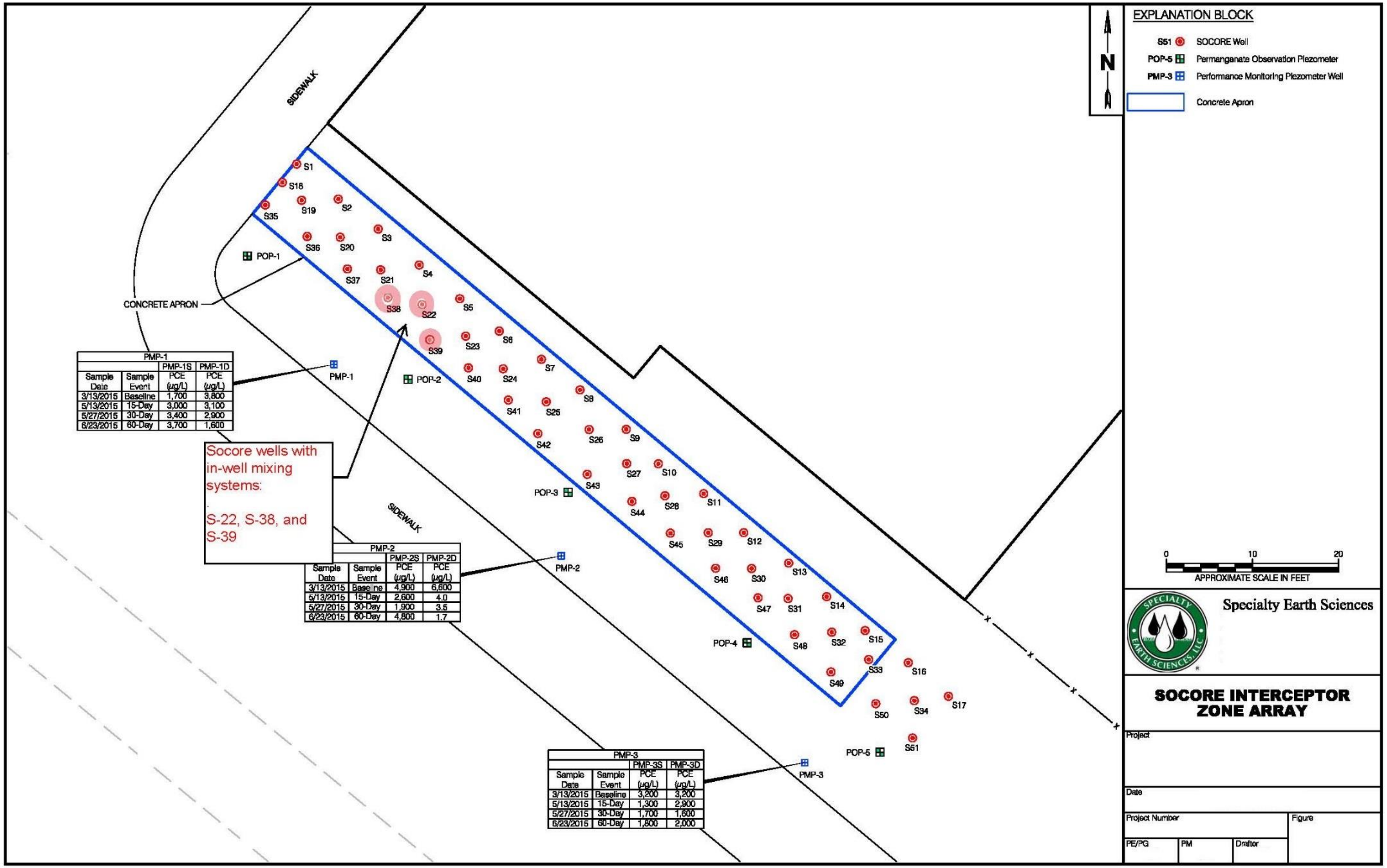
Sample ID	Date Sampled	PCE (µg/L)
PMP-3S	3/13/2015	3,200
PMP-3S	5/13/2015	1,300
PMP-3S	5/27/2015	1,700
PMP-3S	6/24/2015	1,800
PMP-3S	9/03/2015	2,000
PMP-3S	11/19/2015	1,400
PMP-3S	2/26/2016	2,200
PMP-3S	5/19/2016	2,200
PMP-3S	8/30/2016	1,600
PMP-3S	11/17/2016	4,000
PMP-3S	2/14/2017	2,700
PMP-3S	5/05/2017	1,200
PMP-3S	8/15/2017	1,400

PMP-3D - screened 35' - 50' bgs

Sample ID	Date Sampled	PCE (µg/L)
PMP-3D	3/13/2015	3,200
PMP-3D	5/13/2015	2,900
PMP-3D	5/27/2015	1,600
PMP-3D	6/24/2015	2,000
PMP-3D	9/03/2015	2,100
PMP-3D	11/19/2015	1,300
PMP-3D	2/26/2016	360
PMP-3D	5/19/2016	160
PMP-3D	8/30/2016	ND<0.50
PMP-3D	11/17/2016	420
PMP-3D	2/14/2017	160
PMP-3D	5/05/2017	27
PMP-3D	8/15/2017	250



In-well mixing



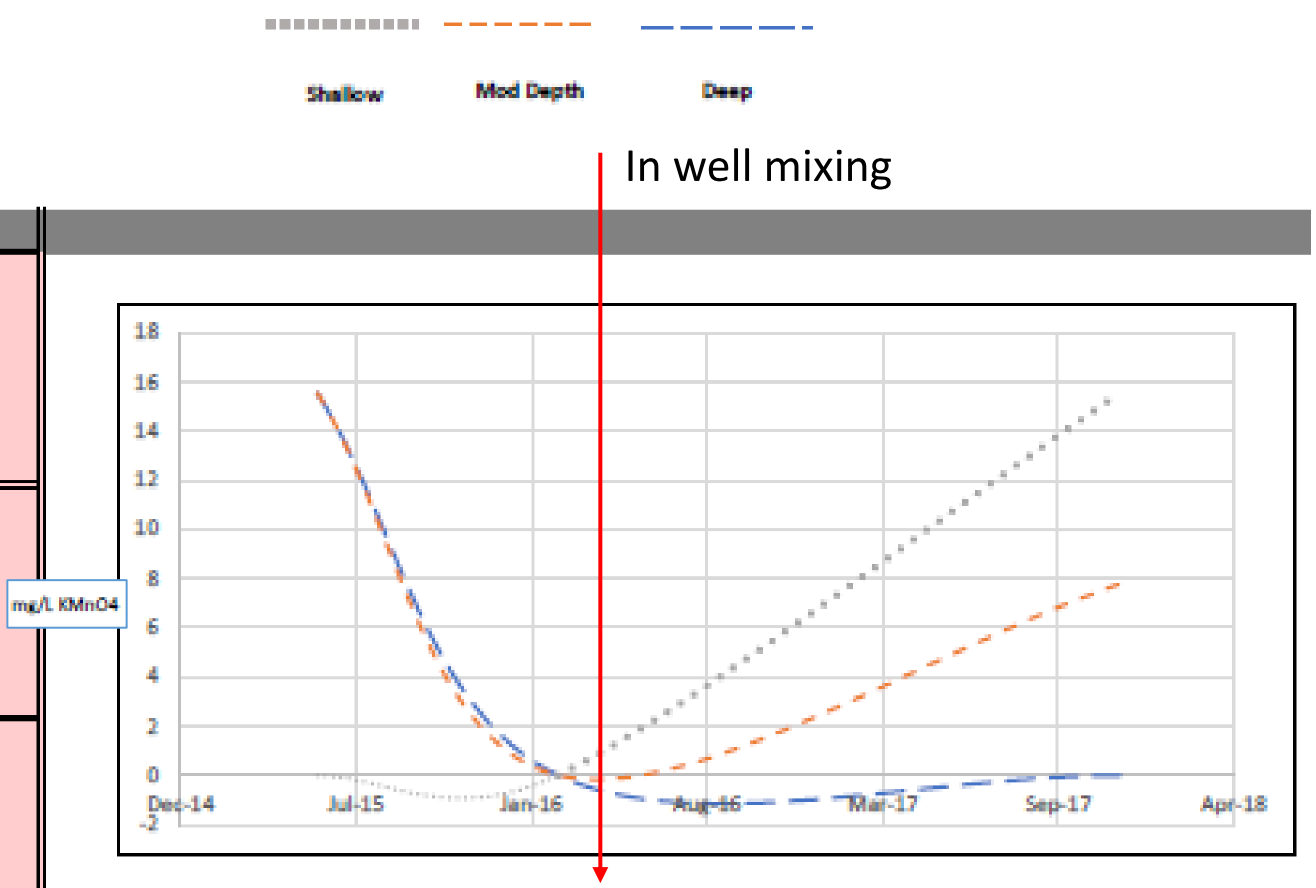
PMP-1			
		PMP-1S	PMP-1D
Sample Date	Sample Event	PCE (µg/L)	PCE (µg/L)
3/13/2015	Baseline	1,700	3,800
5/13/2015	15-Day	3,000	3,100
5/27/2015	30-Day	3,400	2,900
6/23/2015	60-Day	3,700	1,600

PMP-2			
		PMP-2S	PMP-2D
Sample Date	Sample Event	PCE (µg/L)	PCE (µg/L)
3/13/2015	Baseline	4,900	6,600
5/13/2015	15-Day	2,600	4.0
5/27/2015	30-Day	1,900	3.5
6/23/2015	60-Day	4,800	1.7

PMP-3			
		PMP-3S	PMP-3D
Sample Date	Sample Event	PCE (µg/L)	PCE (µg/L)
3/13/2015	Baseline	3,200	3,200
5/13/2015	15-Day	1,300	2,900
5/27/2015	30-Day	1,700	1,600
6/23/2015	60-Day	1,800	2,000

Permanganate Monitoring Data: POP-2

POP-2A	Jun-15	0	0
POP-2A	Mar-16	0	0
POP-2A	Dec-17	15.54	1
POP-2A			
POP-2A			
POP-2A			
POP-2B	Jun-15	15.54	1
POP-2B	Mar-16	0	0
POP-2B	Dec-17	7.77	0.5
POP-2B			
POP-2B			
POP-2B			
POP-2C	Jun-15	15.54	1
POP-2C	Mar-16	0	0
POP-2C	Dec-17	0	0
POP-2C			
POP-2C			



CASE STUDY #4

(South Carolina)

CVOC Source Area Excavation, Soil Venting, Ex-Situ Oxidation…plus a little SOCORE


1. Excavate Source

Baseline data:
9,000-11,000 mg/kg
PCE in source soils

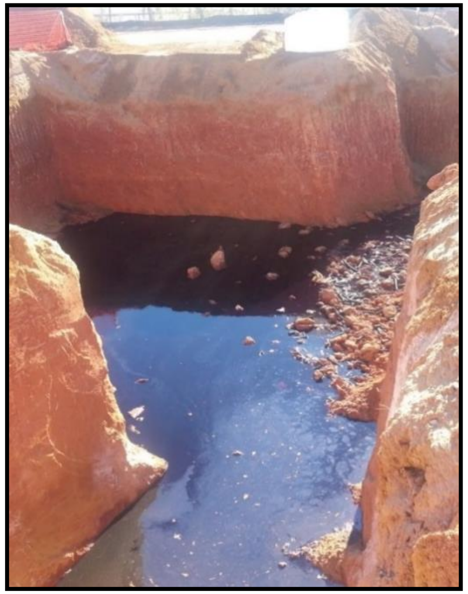
2. Construct soil venting mounds

3. Soil vapor extraction and vapor carbon treatment

SOCORE Enhancement to Alternate Primary Remediation Techniques:

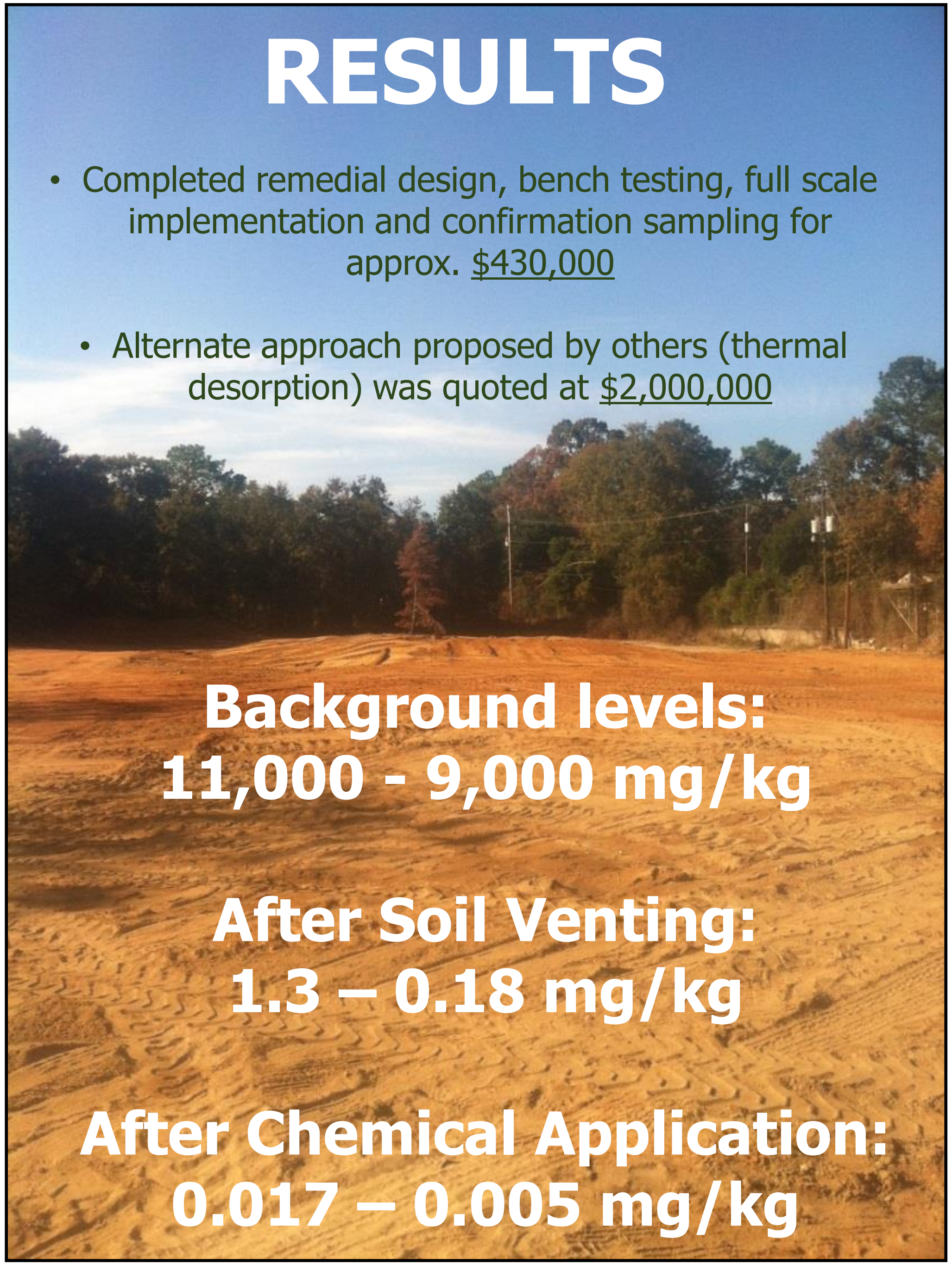
SOCORE Enhancement to Alternate Primary Remediation Techniques:

4. SOCORE cylinders across the excavation floor



5. Ex-situ permanganate treatment of vented source soils and backfill into excavation

SOCORE Enhancement to Alternate Primary Remediation Techniques:



Technical Pearls:

1. Safer and more efficient approach to ISCO
2. Targeted delivery of high concentration reactants
3. Reactive zones and interceptors
4. Addresses problems and challenges encountered with liquid injections
5. Cost to completion less than traditional ISCO injection
6. Implementation by on-site consultant

References:

Links to 3rd party publications can also be found on our website at:

www.sesciences.com/technical-library

Specialty Earth Sciences IP:

US Patent No: 7,431,849
US Patent No: 8,210,773
US Patent No: 8,366,350
US Patent No: 9,061,333
US Patent No: 9,611,421
Japanese Patent No: 6,058,708
US Pat App No: 12-269,520
US Pat App No: 13-088,217
US Pat App No: 13-731,735
US Pat App No: 14-024,046
US Pat App No: 14-920,370
EU Pat App No: 09 826 642.2-1371

Related Publications:

Christenson et al, The Water Center, 2016

Kambhu et al, *Chemosphere*, 2012, 89, 656-664.

Christenson et al, *Chemosphere*, 2012, 89, 680-687.

Woo et al, *Env Tech*, 2009, 30, 1337-1342

Luster-Teasley, *Proceedings of 2007 Natnl Conf on Env Sci and Tech.*

Lee et al, *Chemosphere*, 2007, 74, 745-750

Lee et al, *Chemosphere*, 2007, 71, 902-910

Lee and Schwartz, *Chemosphere*, 2007, 69, 247-253.

Lee and Schwartz, *Chemosphere*, 2007, 66, 2058-2066.

Ross et al *Journal of Environ. Eng.*, 2005, Vol. 131, 1203-1210.

Kang et al. *Ind. Eng. Chem. Res.*, 2004, *43*, 5187-5193.

- Yang 2016 – "To postpone the precipitation of manganese oxides in the degradation of tetrachloroethylene by controlling the permanganate concentration"
  - http://dx.doi.org/10.1080/09593330.2016.1184320
- Chainarong 2016 – "Oxidation of 17B-Estradiol in Water by Slow-Release Permanganate Candles"
  - http://doi:10.1089/ees.2015.0456
- Yao 2016 – "Radial basis function simulation of slow-release permanganate for groundwater remediation via oxidation"
  - https://doi.org/10.1016/j.cam.2016.02.006
- Chanat 2015 – "Treating Methyl Orange in a Two-Dimensional Flow Tank by In Situ Chemical Oxidation Using Slow-Release Persulfate Activated with Zero-Valent Iron"
  - http://doi:10.1089/ees.2015.0110
- Rauscher 2012 – "Using slow-release permanganate candles to remediate PAH-contaminated water"
  - https://doi.org/10.1016/j.jhazmat.2012.09.064
- Kambhu 2012 - "Developing slow-release persulfate candles to treat BTEX contaminated groundwater."
  - http://dx.doi.org/10.1016/j.chemosphere.2012.06.004
- Christenson 2012 - "Using slow-release permanganate candles to remove TCE from a low permeable aquifer at a former landfill."
  - http://dx.doi.org/10.1016/j.chemosphere.2012.06.009
- Woo 2009 "Characteristics of permanganate oxidation of TCE at low reagent concentrations." Environmental Technology
  - http://dx.doi.org/10.1080/09593330902840342
- Luster-Teasley 2009 - "Encapsulation of Potassium Permanganate Oxidant in Polymers"
  - http://books.google.com/books?id=RYE6YKPdFDEC&lpg=PA278&ots=pd_BMxiUaZ&dq=Luster%20teasley%20proceedings%20of%202007&pg=PA278#v=onepage&q=Luster%20teasley%20proceedings%20of%202007&f=false
- Lee 2007 - "Efficacy of controlled-release KMnO4 (CRP) for controlling dissolved TCE plume in groundwater: A large flow-tank study
  - http://dx.doi.org/10.1016/j.chemosphere.2008.10.062
- Lee 2007 - "Characterization and optimization of long-term controlled release system for groundwater remediation: a generalized modeling approach"
  - http://dx.doi.org/10.1016/j.chemosphere.2007.04.037
- Lee 2007 - "Characteristics and applications of controlled-release permanganate for groundwater remediation"
  - http://dx.doi.org/10.1016/j.chemosphere.2006.09.093
- Ross 2005 - "Characteristics of Potassium Permanganate Encapsulated in Polymer"
  - http://dx.doi.org/10.1061/(ASCE)0733-9372(2005)131:8(1203)

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